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

Deliverable D6.2

BEST4HY Regulatory and Standardisation Assessment

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Clean Hydrogen Partnership

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List of Abbreviations

ACEA	Advisory Committee on Environmental Aspects
AFNOR	Association Française de Normalisation
ASR	Automotive Shredder Residue
BoP	Balance of Plant
BPP	Bipolar Plates
CCM	Catalyst Coated Membrane
CCUS	Carbone Capture, Use and Storage
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CFC	Chlorofluorocarbons
CFRP	Carbon Fiber-Reinforced Plastic
CGO	Gadolinium-Doped Ceria
CHP	Combined Heat and Power
CLC/SR	Reporting Secretariat
CRM	Critical Raw Materials
DM-FC	Direct Methanol Fuel Cell
DOE	Department of Energy
EBA	European Battery Alliance
EC	European Commission
EEPS	Electric and Electronical Power Systems
ELV	End of Life Vehicle
EMC/EMF	Electromagnetic Compability/Electromagneric Fields
ENEA	Energia Nucleare Energie Alternative
EoL	End of Life
EPR	Extended Producer Responsibility
EPREL	European Product Registry for Energy Labelling
EU	European Union
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cell Hydrogen technology
GDC	Gadolinium-Doped Ceria
GDL	Gass Diffusion Layer
HFC	Hydrofluorocarbons
ICT	Information and Communication Technologies
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization

ISPRA	Italian Institute for Environmental Protection and Research
JIS	Japanese Industrial Standard
LCA	Life Cycle Assessment
LMT	Light Means of Transport
LSC	Lanthanum Strontium Cobaltite
MEA	Membrane Electrode Assembly
NSB	National Standardisation Body
OECD	Organisation for Economic Co-operation and Development
PA-FC	Phosphoric Acid Fuel Cell
PCR	Product Category Rules
PEMFC	Proton-Exchange Membrane Fuel Cell
PEMWE	Proton-Exchange Membrane Water Electrolyzer
PFSA	Perfluoro Sulfonic Acid
PGM	Platinum Group Material
PSR	Product Specific Rules
PSSA	Polystirene Sulfonic Acid
REE	Rare Earth Element
RoHS	Restriction of Hazardous Substances
ScSZ	Scandia-Stabilized Zirconia
SDO	Standards Developing Organization
SLI	Starting, Light, and Ignition
SMB	Standardization Management Board
SME	Small-Medium Enterprise
SOFC	Solid Oxide Fuel Cell
s-PEEK	Sulfonated polyetheretherketone
TC	Technical Committee
WEEE	Waste from Electrical and Electronic Equipment
WG	Working Group
WSR	Regulation on Waste Shipment
YSZ	Yttria Stabilized Zirconia

Executive Summary

This document presents the activities carried out during WP6 of the BEST4Hy project, specifically to Task 6.1 - Regulatory aspects (EU and extra EU vision) and Task 6.2 - Standardisation aspects.

The partners involved are RINA-C and ENVIRONMENT PARK with the support of the entire Consortium and especially Hensel Recycling and EKPO.

Understanding the requirements of EU rules about how to handle end-of-life fuel cell and hydrogen (FCH) technologies and their content of rare and non-rare elements is the main goal of Task 6.1. This report offers a regulatory assessment looking at the EU legislation starting with the results of project HyTechCycling [[1]]. Members of BEST4Hy Advisory Board have also contributed in an effort to gain a better understanding of the legal systems in Japan, the United States, and other non-EU nations.

To understand the standards to be applied to FCH and other types of technologies containing similar precious/rare/hazardous materials as in fuel cells, a standardization inventory has been undertaken within the remit of Task 6.2. The inventory includes topics such as design technology (eco-design), lifetime definition, disassembly, and end of life management.

In Chapter 2, it is discussed how to handle rare and non-rare materials found in end-of-life FC technologies while also referencing novel ways. The regulatory assessment has also been completed for some Extra-EU nations (USA, Japan, Korea, Singapore).

A standardization assessment is carried out in Chapter 3. After providing a technical review of PEMFC, SOFC, and EoL technologies, a study of their essential raw materials and industry standards was conducted. This was followed by the identification of the potentially applicable standards on FC EoL and Ecodesign.

[1] H2020 HyTechCycling project 2016-2019, http://HyTechCycling.eu/

Chapter 4 presents the results of a survey that was distributed to partners and other FCH technology manufacturers in order to obtain direct information complementing the desktop review.

Finally, in Chapter 5, the gaps in the standardized environment have been identified, as a starting point for a standardization and regulatory road mapping.

1 Regulatory Assessment

This section gives a general overview of the EU regulations on how to treat end-of-life hydrogen technologies and their critical material content.

BEST4Hy's regulatory assessment follows an approach strategy via stakeholders' involvement, summarised as follows:

- EU regulatory assessment related to how to treat end-of-life rare/not-rare materials contained in FC and other hydrogen technologies: analysis of EU waste regulations, barriers and new approaches (outcomes of HyTechCycling project) integrated with new regulations on resource management;
- Extra-EU regulatory assessment related to how to treat end-of-life hydrogen technologies: via dedicated survey and calls with BEST4Hy AB and stakeholders;
- Main markets to focus on: Japan (via Toyota Motor, IAE-Institute of Applied Energy partner of eGHOSt/SH2 projects), China (via EKPO semi-automated fuel cell stack assembly line at its Suzhou site in the third quarter of 2022), USA (via HRD), Singapore (via ERIAN);
- EU market via BEST4Hy partners (EKPO, Elcogen), H2 Clusters (Tweed – Belgium; Tenerrdis – France), eGHOSt/SH2 projects (Symbio FC), EVERYWH2ERE project (Powercell);
- Interaction with Working Groups on regulation/standardization (EU and Regional, via EKPO contacts);
- Interaction with Working Groups on ELV modification.

A preliminary survey has been also launched in connection to task 6.2 with the stakeholders mainly to assess the manufacturers' approach to the end-of-life phase of their products and their awareness of the standardisation framework.

The survey, explained in section 4, was the opportunity to understand the regulatory knowledge from the companies' perspective.

1.1 EU regulatory assessment related to how to treat end-of-life rare/not-rare materials contained in FCH technologies: HyTechCycling main results and outcomes

The activities performed during the first 6 months were focused on analysing the documents developed within the HyTechCycling project and in particular the major barriers relating to existing regulations as well as how to classify FCH technologies according to waste regulation classes.

HyTechCycling[2] project, ended in 2019 and focusing on recycling and dismantling processes of FCH technologies, has analysed the European regulations directly or indirectly referring to the FCH technologies as well performed direct consultations with the involved stakeholders (manufacturers, recycling centres, distributors, end-users).

The project's methodology was firstly to identify the main FCH stack and system elements and to analyse, later, related regulations and barriers affecting the end-of-life stage management of the technology in view of an integrated approach and the different key actors involved in the product life cycle.

Each phase of the FCH life can influence the product management at its end-of-life stage and several main factors need to be considered, from the materials' selection to the eco-design and the waste regulation management. FCH system analysis considers FCH stack, BoP components, power conditioning, batteries, cabinet, FCH product, FCEV, CHP.

The following directives were analysed:

- Eco-Design Directive has to be considered in the whole FCHs system design, but also for the materials selection both FC stack and BoP components;
- REACH Regulation is to be considered in stack and BoP materials selection;
- RoHS Directive is specific to material selection in power control systems;
- WEEE Directive is related to electric and electronic parts in a fuel cell system;
- Hazardous waste Directive has to be used for FC stacks and BoP components with hazardous materials;
- ELV Directive apply for FCEVs;
- Batteries Directive is specific for EoL batteries installed in FCH system.

The table below reports and links the legislation on material design and EoL stage with each fuel cell systems:

[2] H2020 HyTechCycling project 2016-2019, http://HyTechCycling.eu/

Table 1: Legislation reference to life cycle of an FCH system from HyTechCycling.

Life cycle of FCH	DIRECTIVES	FCH stack	BoP components	power conditioning	batteries	cabinet	FCH product	FCEV	CHP
DESIGN	Eco Desingn Directive						x	x	x
materials selection	REACH Regulation	x	x				x		
	RoHS Directive			x			x		
end of life managment	WEEE Directive	x	x	x			x		
	Landfill directive	x	x	x	x	x	x	x	x
	Hazardous waste Directive	x	x						
	Batteries Directive				x			x	x
	ELV Directive							x	

General directives have been found on design, material selection and end-of-life management of products/energy products or, in some cases, of special products such as batteries and vehicles. However, no directive specifically refers to FCH technologies, thus resulting in lack of clarity and difficulty of application.

After the second step of the HyTechCycling project of stakeholders' consultations, in view of the regulations analysis, the main barriers for the deployment of FCH technologies related to present legislations are summarized[3] below:

Barrier on system design

FCHs manufacturers have to implement and provide evidence of eco-design. Specific chapters in the eco-design Directive on FCHs technologies are required otherwise the FCH manufacturers may incur in a negative impact of the product. Another fundamental aspect tied to eco-design is related to the choice of materials during the design process, which can impact on the cost of technology positively.

Barrier related to Eco-design Directive

Ecodesign for resource efficiency can benefit consumers by making products more durable or easier to repair. It can help recyclers to disassemble products in order to collect valuable materials. It can contribute to save resources that are valuable for the environment and economy. Market signals are, however, not always sufficient to make this happen, in

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[3] Regulation framework analysis and barriers identification [D2.3], HyTechCycling

particular because the interests of producers, users and recyclers are not necessarily aligned. It is, therefore, essential to promote and boost improved product design, while at the same time preserving the internal market and enabling innovation.

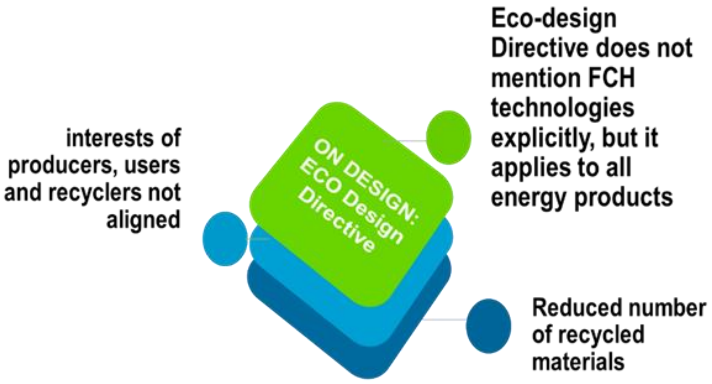

Figure 1: Analysis of barriers in the ECO Design Directive.

Barriers on materials selection

The present legislation on hazardous materials poses restrictions in the selection of substances. This implies the need for manufacturers to take into serious consideration this requirement because it might preclude the marketing of these systems. Barriers related to REACH Regulation and RoHS Directive.

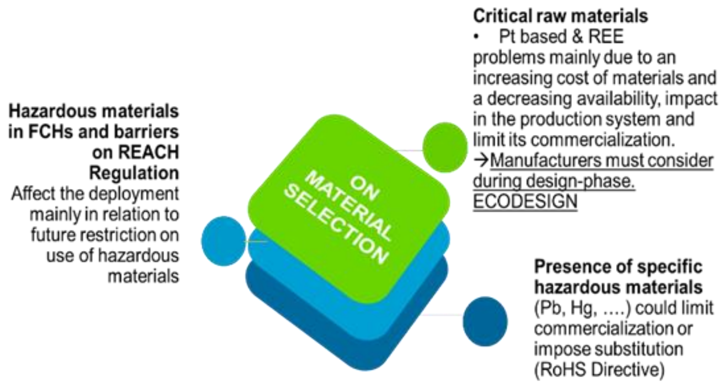

Figure 2: Analysis of barriers on material selection.

Barrier on End-of-Life management

Recycling targets can be too restrictive if the FCH developers will not pay attention to them during the design phase and this could affect the technology's image. However, the WEEE Directive poses an important issue due to the exclusion of large-scale stationary industrial tools from the Directive. Therefore, FCH developers should focus on strategies for end-of-life management of the stack to limit any waste disposal and for the following recovery and recycling procedures taking them into account during the eco-design phase.

Lack of a specific FCH Directive

Some Directives include FCH products or must be taken into account when working with a FCH system, but the creation of a more detailed and relevant FCH regulation is needed.

In particular, in HyTechCycling some recommendations[4] on EU regulatory framework are highlighted and proposals of new laws come as results:

Hazardous and critical materials:

1. Reduce their use by imposing a limited amount, compatible with the application, otherwise imposing a socio-economic assessment to justify their use;
2. At the end, prohibit the use of hazardous materials.

Eco-design:

1. Harmonize the design process in order the facilitate the dismantling stage;
2. Improve the quality and durability by imposing a minimum standard;
3. Modular conception;
4. Imposing a rate of recycled materials used;
5. Clear labelling.

Recyclability charts:

1. For each sub-system, apply a dismantling and recyclability rating.

Agreements:

1. Develop a strong network between FCH manufacturers and recycling centres;
2. Win-win: manufacturers buy materials and components at a low price; recycling centres assure to have a new market.

[4] Report on feedback to new technologies and strategies and focus on new business model from FCH actors [D5.2], HyTechCycling

Specific and harmonized regulations on FCH, covering all the different aspects above mentioned for the sustainability and the end-of-life FCH systems management, could help the different stakeholders align their needs and innovate the market. Regulations could also boost the innovation technologies for recovery and recycling processes, as well as eco-design and manufacturing steps.

Recommendations, together with the needs required by each involved stakeholder are summarized in the figure below[5]:

Figure 3: Stakeholders role and recommendations.

The HYTECHCLING project offers a first overview of the current legislation landscape for FCH systems and suggests how to proceed with the analysis.

At this stage of BEST4Hy, the identified directives are now explored to verify updates, state-of-the art, shortcomings to have a regulation framework completely covering the FCH technologies in all life cycle stages. Legislations dedicated to the circular economy topic, like waste management or critical raw materials, need to be considered.

[5] Guidelines on re-adaptation of existing recycling centres [D5.3], HyTechCycling

1.2 EU Regulatory Assessment related to how to treat end of-life rare/not-rare materials contained in FCH technologies: new approaches

The section covers existing strategy documents, regulations and directives, including those under revision, and concerning the following issues:

- Circular economy;
- Ecodesign;
- Waste and resources;
- Critical raw materials.

Considering the field of application of fuel cell technologies and similar systems/groups of products, this review also covers:

- End of Life of vehicles;
- Batteries.

1.2.1 The (New) Circular Economy Action Plan

Circular Economy is at the heart of the Green Deal. Codified within the Action Plan for the Circular Economy (European Commission, 2015) and the New Action Plan for the Circular Economy (European Commission, 2020)), circular economy aims to limit the impact of the economy on the environment by using less resources, keeping them in use for longer and regenerating as much as possible the environment. In the 2020 Action Plan, initiatives along the entire life cycle of products are targeted, from eco-design to circular processes, so to push sustainability of products and approaches. A few specific sectors are targeted, including electronics and ICT (mostly consumer products) but also expanding sectors such as electric vehicles and batteries.

The policy mainstreaming of the circular economy approach through the Action Plan is implemented through a re-assessment of existing Directives and Regulations and the inclusion of circular economy principles in proposals for new approaches and/or for new regulations on new areas such as batteries. For example, the Waste Shipment Regulations have been reviewed in November 2021 (see section 2.2.5) and the review of the Eco design Directive has spurred a Sustainable Products Initiative (see section 2.2.2).

1.2.2 Ecodesign Directive (Energy Products Directive)

The Ecodesign Directive (Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of Eco Design requirements for energy-related products) is currently under revision.

The EU is rethinking its approach on sustainability of products in general, starting from the experience gained with the 2009/125/EC Directive. So while the latter only focused on certain energy related products[6] the new Regulation would cover any product commercialised in Europe, as a cornerstone of the Sustainable Products Initiative. Launched in March 2022, the initiative has amongst its objective (target: year 2030) to ensure that:

- A significant part of the products on the EU market are designed to be more durable and energy- and resource efficient, reparable, recyclable, and with preference for recycled materials;
- Companies from all over the world are able to compete on a level playing field without being undercut by others that leave society to deal with their environmental damage;
- Companies can access environmental performance data to ensure environmental sustainability and circularity of their products and business models.

Amongst the key actions are the promotion of design to reduce products' environmental impact; the improvement on product sustainability information for consumers and supply chain actors and the promotion of more sustainable business models.

With the launch of the initiative, the "Ecodesign requirements for sustainable products", a proposal for a new Ecodesign for Sustainable Products Regulation was also published.

The proposal establishes a framework for setting eco-design requirements for specific product groups to significantly improve their circularity, energy performance and other environmental sustainability aspects, so to promote more sustainability over the whole life cycle of goods placed in the market. This could also increase recycling output in the near term, boost demand for recycled goods, increase their recycled content, and increase recycling rates in the EU.

The framework will allow for the setting of a wide range of requirements, including:

- Product durability, reusability, upgradability and reparability;
- Presence of substances that inhibit circularity;
- Energy and resource efficiency;
- Recycled content;
- Remanufacturing and recycling;
- Carbon and environmental footprints;

[6] The list of products to which the Ecodesign Directive refers can be found at this link: https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/product-database_en

- Information requirements, including a Digital Product Passport, which will contain data on the environmental sustainability of the product and could be used by consumers and procurers for comparing their buying options.

The application of the proposed new Regulations will follow a series of working plans, of which, currently, the 2022-2024 is active.

The document builds on work done since the adoption of the first Ecodesign Directive, but also covers the work required under the Energy Labelling Framework Regulation (EU/2017/1369) and takes stock of the progress made with the European Product Registry for Energy Labelling (EPREL).

The working plan 2022-2024 covers new energy-related products and updates and increases the ambition for products that are already regulated, as a transitionary measure until the new regulation enters into force. It addresses consumer electronics, such as smartphones, tablets and solar panels, the fastest-growing waste stream. It also includes an indicative list of new energy-related product groups to be studied, amongst which chargers for electric vehicles.

Overall, the Ecodesign Directive is enlarging its scope to large distribution/consumer products in the energy-using category. Noticeably, batteries are not within the scope of this work as yet, most probably as specific regulatory instruments are under development for these systems (see below section 2.2.5)

1.2.3 ELV (Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles)

Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles – the End-of-life vehicles (ELV) Directive has regulated the reuse, recycling and recovery of vehicles reaching the end of their life, as well as regulating the reusability, recyclability and recoverability of vehicles put on the market. An evaluation of the Directive in 2021 has started the process of revision, which should result in a proposal for a revised Directive due in 2023.

The revision takes into account targeted modification of the ELV Directive to boost recycling and reuse that means:

- Have better alignment with EU waste legislation (clearer definition of recycling);
- Reduce the number of “missing vehicles” through new enforcement measures;
- Have new, more ambitious targets for reuse and recycling, per materials such as plastics, and promotion of remanufacturing;
- Set a fully-fledged Extended Producers’ Responsibility system for the financing of recycling/reuse of all materials;
- Facilitate access of dismantlers to information on parts and materials used in cars;
- Have better harmonization of reporting across the EU Member States.

Batteries are not covered by the ELV legislation in terms of recycling targets, but only mentioned for the presence of toxic materials (cadmium) and consequent exemption (Annex II) for spare parts for older electric vehicles.

Removal of catalysts also is listed as depollution operation required for the promotion of recycling (Annex I).

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1.2.4 The "Critical Raw Materials Act"

Published in March 2023, the Critical Raw Materials Act[7] aims to open the road for a specific European regulation on critical raw materials (CRMs), strengthening the EU value chain on CRMs. It represents the European commitment to ensure a sustainable, independent access to critical raw materials and to guarantee the EU control on the CRMs supply chain, supporting their role in the green and digital transition.

The Critical Raw Materials Act and future regulation development result from the European Action Plan on Critical Raw Materials[8] and related research studies commissioned by EC: "Critical Raw Materials for Strategic Technologies and Sectors in the EU – A Foresight Study"[9] (published in 2020) and its evolution into "Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study"[10] (published in March 2023). This latter gives interesting perspectives of the CRMs role in the European economy, providing scientific background on the potential supply risk of material resources for a set of 15 key technology's value chains across five strategic sectors: renewable energy, electromobility, industrial, digital, and aerospace/defence. The report considers the current energy crisis and the EU objectives to become energetically independent from the Russian oil and gas, and by doing so, accelerating the sustainable energy transition. In this regard, the raw materials included in main strategic key technologies become Strategic raw materials to guide the EU energy transition and the key sectors development. For this reason, within the Critical Raw Materials Act, the updated list of the CRMs and the new list of Strategic Raw Materials[11] have also been released (see

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[7] Critical Raw Materials Act (https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1661)

[8] Action Plan on Critical Raw Materials (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0474)

[9] Critical Raw Materials for Strategic Technologies and Sectors in the EU – A Foresight Study, European Commission, Joint Research Centre, 2020, doi: 10.2873/58081

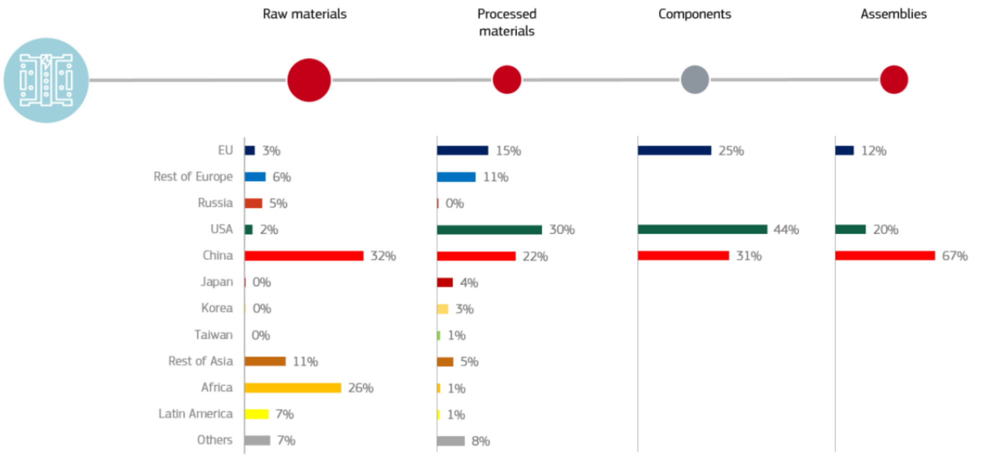
[10] Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study, European Commission, Joint Research Centre, 2023, doi: 10.2760/386650 , 10.2760/334074

[11] COM_2023_160_1_EN_annexe_proposition_part1_v6.pdf (europa.eu)

section 2.3 for the complete lists of materials). In these lists, Cobalt, Nickel and PGMs are classified as both critical and strategic raw materials.

By further analysing the JRC study, the role of hydrogen fuel cells in the EU sustainable economy is widely explored. In favour of a regulation update, the above-mentioned study provides an overview of supply risks; bottlenecks and key players are also reported.

As shown in Figure 4, Europe produces less than 3% of total CRMs used in fuel cells globally, while high risk of supply issues is estimated for the raw materials for which the EU is highly dependent from China and Africa.



Note: In the case of components, the graph represents combined categories for Europe (EU27 together with Rest of Europe), North America (USA + Canada), and Asia (China, Japan, Korea, Taiwan, and Rest of Asia) presented at the level of the main source.

Figure 4: Overview of supply risks, bottlenecks, and key players along the supply chain of fuel cells as reported in the "Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study", JRC, 2023.

Following the raw materials' supply analysis (Figure 5), high risk is also associated to Lanthanum, Yttrium, while slightly lower risk is associated to Platinum and Cobalt, and much lower risk to Nickel.

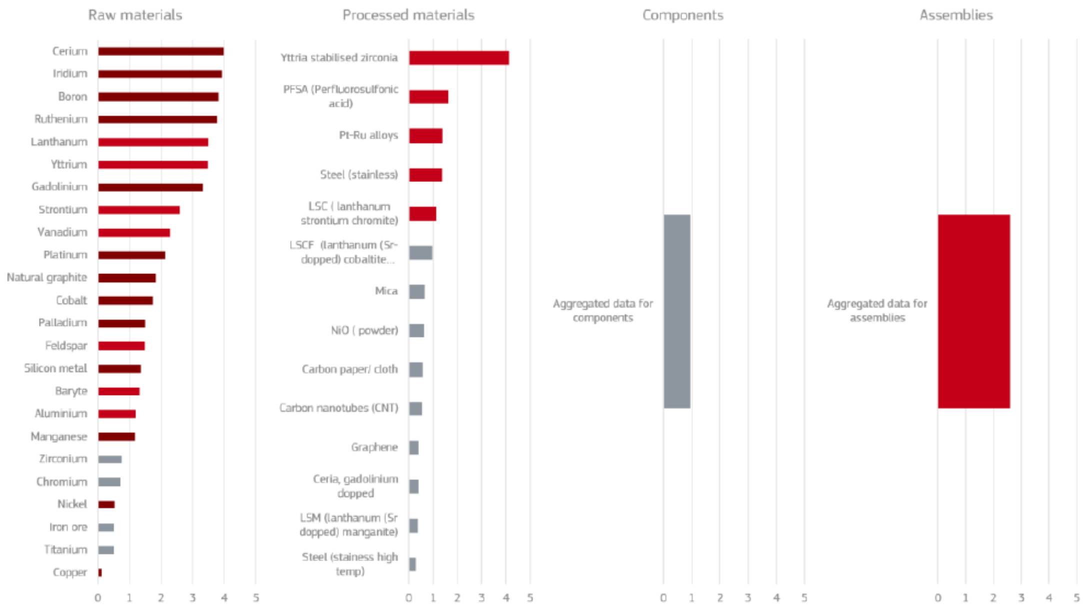


Figure 5: Detailed supply risk of all elements in the fuel cells supply chain, from the "Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU – A foresight study", JRC, 2023.

High risks are also depicted in the processed materials and even in the assemblies, where mainly China and USA are prevailing in the global market. On the other hand, EU is quite independent in the step of FC's components production, counting 25% of the global production.

The risks ascertained, exacerbated by the increasing number of FCH technologies expected in the next period 2030/2050 (e.g., little more than 1 million of FCEVs are expected in 2050 considering a low demand scenario, around 1,5 million of FCEVs for a high demand scenario), highlight the need to increase the diversification of materials supply, the improvement of the EU manufacturing opportunities, as well as the need to boost recycling, reuse and substitution of materials. Indeed, finding equally efficient and available alternative materials to platinum as catalyst is not realistic, thereby **recovery and recycling PGMs appears to be the best sustainable and economic solution**. Efforts should focus on R&D to improve the efficiency of recycling technology and the cost of recycling. A further recommendation from the JRC study is to foster international collaboration and standardisation activities, creating partnerships along the value chain and **accelerating the technical standards that cover the entire life cycle of a fuel cells** (from manufacturing to recycling and even emission standards for hydrogen traded internationally).

Other support to the topic comes from industry. The act reflects also the needs of the European metals industry, which already expresses its interest in the topic during the public consultation stage. Eurometaux[12], Europe's metals association, representing mining, processing, recycling companies in Europe, made some recommendations on the future CRMs regulations and strategy focusing on the ambition of Europe to increase its role as international competitor in the CRMs global market and to become the global leader for high-quality metals recycling. In the context of the circular economy, industry highlights the importance of setting EU wide strategic targets for 2030 on own supply of extracted/recycled, refined minerals and level of import diversification, enabling the establishment of a long-term metals strategic autonomy[13].

It is also recognised that overall, the recycling of FCs represents a new business for recyclers and a potential topic for research to consider. Legislation could address the recycling aspect in terms of design, material selection and end-of-life. Recycling, reuse and remanufacturing could help to reduce dependencies of CRMs supply from third countries and, therefore, need to be further explored. Moreover, global standardisation framework covering different issues, from the performance to the safety or permitting, could enable component compatibility and inter-operability, could contribute to reducing costs and increasing the availability of components.

Based on these preliminary considerations and studies, the Critical Raw Materials Act aims to propose a set of actions with the objectives of ensuring access to a secure, diversified, affordable and sustainable supply of critical raw materials for the European economy. The identified actions focus on both internal and international measures. The **internal actions** are summarised below:

Setting clear priorities of actions: the updated list of critical raw materials and a new list of strategic raw materials for the EU economy have been defined, but also embedded in the EU law. Clear targets by 2030 for EU capacity to be built up are also identified along the strategic raw materials supply chain:

- At least 10% of the EU's annual consumption for extraction,
- At least 40% of the EU's annual consumption for processing,
- At least 15% of the EU's annual consumption for recycling,

[12] Eurometaux: European collective metals association, https://eurometaux.eu/
[13] https://eurometaux.eu/media/2zylte5v/critical-raw-materials-act-summary-of-eurometaux-recommendations-25-11-22.pdf

- Not more than 65% of the Union's annual consumption of each strategic raw material at any relevant stage of processing from a single third country.

Creating secure and resilient EU critical raw materials supply chains: actions to simplify the administrative and the permitting procedures for all critical raw materials in the EU, together with the promotion of Strategic Projects on that topic and national programmes for geological resources exploration.

Ensuring that the EU can mitigate supply risks: monitoring of the critical raw materials supply chain among the Member States and audit on strategic raw materials supply chain for large companies.

Investing in research, innovation and skills: partnerships and Raw Materials Academy.

Protecting the environment by improving circularity and sustainability of critical raw materials: environmental, human rights and human labour protection along the value chain supply, especially in third countries. Enhancing the collection and recovery rate of critical raw materials in each country, boosting the recycling and use of secondary materials.

The **international engagement** actions mainly include the diversification of the European imports of critical raw materials and strengthening specific trade actions to ensure a stable critical raw materials supply. A set of main trade actions is listed below:

- CRM Club: establish a raw materials alliance with partners to strengthen supply chains and diversify sourcing.
- Strategic Partnerships on Raw Materials: expand the network of strategic raw materials partnerships.
- Trade and Investment Agreements: leverage and expand trade agreements as regards raw materials extraction, processing and trade.
- Global Gateway: support critical raw material supply projects, including on infrastructure, connectivity and sustainability.
- Enforcing Trade Rules: continue to combat unfair trade practices, especially when they concern trade investment in or access to critical raw materials.

For the specific role of hydrogen fuel cells as key technology, the EU trade actions will also aim to enhance the collaboration with South Africa for more predictable legal environment for trade and investment, strategic raw materials partnership with countries with important reserves and to support investments in South African energy infrastructure.

Considering the European regulation framework, the proposed Regulation on CRMs has been presented jointly with the Net Zero Industry Act[14] with the objectives to reach the net-zero industries and the European industry competitiveness targets (Green Deal Industrial Plan[15]).

1.2.5 Waste Shipment Regulation

The EC adopted the proposal[16] on a new Regulation on Waste Shipment (WSR) in November 2021.

The WRS Regulation[17] refers to the European system of waste shipments within its borders, including secondary and other valuable raw materials. The aim of the Regulation is to cover the transboundary shipments of waste with environmental protection, reduce human health risks and pursue a legal clarity and harmonization, especially with third countries and considering new national restrictions; it complies with the International Basel Convention and the OECD control system for the movements of hazardous and non-hazardous wastes among EU Member States and third countries.

The new proposal reflects the waste market needs of reusing and recycling waste streams to support the circular economy transition and recycling industries, measures to discourage illegal shipments, improve digitalization procedure of EU waste exports and guarantee environmental and social waste management.

Currently, several materials are shipped in the form of waste and are meant to be disposed of in other countries, resulting in a loss of valuable resources rather than supplying the recycling industries in the country of origin.

The WRS revision would propose to prohibit the waste shipment with disposal destination to any other third countries and the export of non-hazardous waste to non-OECD countries, other than exceptional cases (hazardous waste exports for recovery is already prohibited).

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[14] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1665
[15] https://ec.europa.eu/commission/presscorner/detail/en/ip_23_510
[16]https://environment.ec.europa.eu/topics/waste-and-recycling/waste-shipments_en#overview
[17] Regulation on Waste Shipment (https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32006R1013)

The prohibitions, supported by a strengthen monitoring of waste streams through the improvement of an electronic tracking system and notification procedure, have the objectives to encourage the recovery and recycling materials processes within the waste production country and boost the national recycling industries. In particular, this support for the recycling materials answer to the European Circular Economy Action Plan with a focus on the critical raw materials identified as high economic value material to preserve and transform into secondary raw materials, contributing to the diversification of sources of supply for the EU industries.

Several open public consultations and workshops took place in the past year to investigate stakeholders' evaluation and impact assessment of the WRS regulation. Their findings were quite aligned between stakeholders and Member States and different policy options were discussed, finally deciding on a policy where both targeted and structural regulation changes are planned.

The main proposed measures are intended to facilitate the intra-EU shipments in line with the circular economy objectives, support the EU's objective to stop exporting its waste challenges to third countries, and contribute to better addressing illegal shipments of waste, without risking excessive costs or disruption. Figure below summaries the main measures proposed by this preferred option:

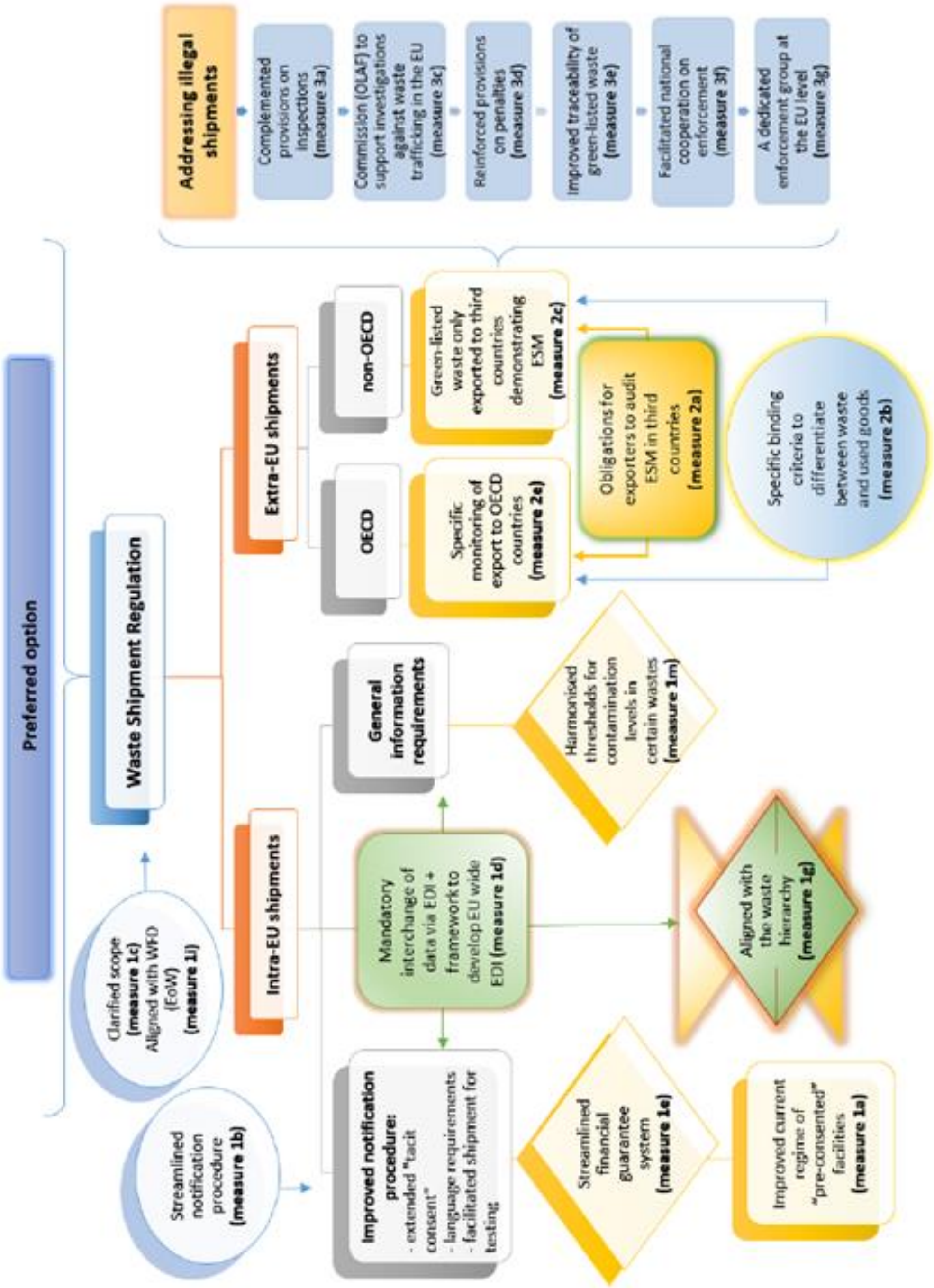

Figure 6: New measures in the Waste Shipment Regulation proposal.

The WRS Regulation proposal has been under revision by the EU Parliament in January 2023. A first legislation revision has provided a series of reviews, among which some specific recommendations are meant to introduce mandatory recycled content targets for products gathered in a report to be released within 2 years the regulation becomes operational.

According to the WRS proposal, more restrictions will be required in the waste shipments, but no specific limitations can be now addressed to PGMs. On the contrary, the proposal intends to promote the secondary raw materials market and support the CRMs within the European economy and supply. Thus, the WRS aims to be aligned with the other European directives on circular economy and critical raw materials (Critical Raw Materials Act above mentioned), encouraging measures and new legislation for the recovery and recycling of raw materials, identification of new secondary raw materials streams and its valorisation within the market.

1.2.6 New EU Battery Legislation

A new regulation proposal[18] is under validation procedure screening by the Parliament and Council with foresight to replace the existing Batteries Directive from 2006 (DIRECTIVE 2006/66/EC). This new EU battery legislation proposed by the EC in December 2020 addresses all types of batteries in relation to social, economic, and environmental issues with a life cycle thinking approach. The new proposal responds to the European Green Deal goals for a more sustainable, circular, low-carbon and safe Europe. At the moment, the battery industry is required to be more competitive and capable to offer strategic technology able to reach the European climate neutrality goals, run the clean energy transition and fuel independence.

In this purpose, the new legislation aims to provide measures to ensure an overall monitoring of the batteries along their entire life cycle, enhancing collection and recyclability, as well as introduction of secondary material targets in the new batteries manufacturing process and strict social and environmental controls. This regulation will operate jointly with other related legislation, in the form of cradle-to-grave regulation

[18] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_7588

framework that will become fully operational only by the end of 2028 (2024-2028 period for secondary legislation adoption).

The proposed new measures[19] effect from previous activities of stakeholders' involvement and policy engagement figuring in the European Battery Alliance (EBA)[20] and the Strategic Action Plan on Batteries. The Strategic Action Plan on Batteries' main goal is to make Europe a global leader in sustainable battery production and use, in the context of the circular economy. From its side, the EBA has the role to build an innovative, sustainable and globally competitive battery value chain. The value chain approach faces multi-dimensional challenges: technology, business models, supply chain, human capital, regulation and industrialization are network nodes. All dimensions are interlinked, so they could and should be addressed simultaneously (Figure 7).

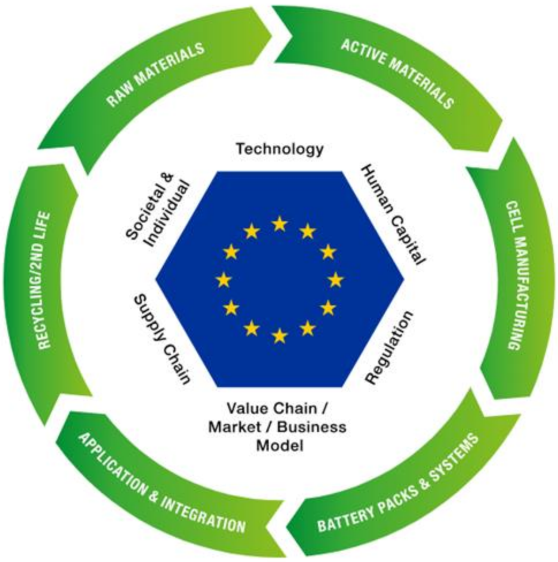

Figure 7: European Battery value chain approach of the EBA.

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[19]https://www.europarl.europa.eu/news/en/press-room/20221205IPR60614/batteries-deal-on-new-eu-rules-for-design-production-and-waste-treatment
[20] https://www.eba250.com/legislation-market/eu-legislation/

Going more in detail into the proposal, the new articles refer to all type of portable batteries, SLI batteries (supplying power for starting, lighting or ignition of vehicles), light means of transport (LMT) batteries (providing power for the traction to wheeled vehicles such as electric scooters and bikes), electric vehicle (EV) batteries and industrial batteries. It gives relevance to raw materials and recycling issues, but aims to cover the manufacture, design, labelling, traceability, collection, re-use, and recycling of batteries throughout their lifecycle:

Customer information and traceability

1. From 2027, battery will have to be labelled with the name of the manufacturer, type of battery, date of manufacture, presence of hazardous substances and other information that facilitates recycling or reuse. Manufacturers will be required to include information with end-of-life batteries that minimize waste and contribute to the reuse or recycling of their material content. They must also provide information about how automotive batteries should be safely dismantled, transported and recycled. In addition, they will be obliged to disclose the environmental and health impact of battery contents;
2. LMT batteries, industrial batteries with a capacity above 2 kWh and EV batteries will also be required to have a "digital battery passport" including information on the battery model as well as information specific to the individual battery and its use;
3. Reconditioned or reused batteries must be accompanied by documentation regarding their status, a change of ownership certificate and technical documentation;
4. Once the new law enters into force, sustainability requirements on carbon footprint, recycled content and performance and durability will be introduced gradually from 2024 onwards. Carbon footprint declaration and labels will be obligatory for EV batteries, LMT batteries and rechargeable industrial batteries with a capacity above 2kWh;
5. According to the deal, all economic operators placing batteries on the EU market, except for SMEs, will be required to develop and implement a so-called "due diligence policy", consistent with international standards, to address the social and environmental risks linked to sourcing, processing, and trading raw materials and secondary raw materials.

New rules for collection, recycling and repurposing

1. A more comprehensive regulatory framework on Extended Producer Responsibility will start applying by mid-2025, with higher collection targets being introduced over time. For portable batteries, the targets will be 63% in 2027 and 73% in 2030, while for batteries from light means of transport, the target will be 51% in 2028 and 61% in 2031;
2. All collected batteries must be recycled and high levels of recovery must be achieved, in particular, valuable materials such as copper, cobalt, lithium, nickel and lead. This will guarantee that valuable materials are recovered at the end of their useful life and brought back in the economy by adopting stricter targets for recycling efficiency and material recovery over time. Material recovery targets for lithium will be 50% by 2027 and 80% by 2031. The EU is seeking to set a 90% recycling rate for cobalt, copper, nickel, and lead from 2026;
3. All waste LMT, EV, SLI and industrial batteries must be collected, free of charge for end-users, regardless of their nature, chemical composition, condition, brand or origin;

Co-funded by the European Union

4. Recyclers will have to report annually on the quantity of batteries they handle and recycle, as well as the recycling rates of the various materials extracted. It will also be a requirement to measure the efficiency of their recycling processes;
5. The export of used batteries outside the EU will only be permitted if the recipient's battery management procedure meets the EU's requirements.

New rules for production

1. As early as 2027, the proposed EU legislation will require manufacturers to provide transparent information on the quantity of recycled cobalt, lithium, nickel, and lead in new car batteries. The required amount of recycled cobalt and lithium will more than double from 2030 to 2035;
2. Manufacturers will be required to increase the number of portable batteries they collect by 45% by 2026, and by 70% by 2030.
3. New circular partnerships between battery manufacturers and recyclers will be required to enhance the circularity of the batteries' life cycle;
4. Among other measures, recycling will need to increase, more recycled materials will be required in the production of new batteries. Minimum levels of recovered cobalt (16%), lead (85%), lithium (6%) and nickel (6%) from manufacturing and consumer waste must be reused in new batteries;

The new proposal appears a reasonably complete and progressive regulation, consisting with the current innovation of the battery sector. Even if the regulatory framework adoption will take time to be effective, it appears clear the effort to comply the circularity topic required in the European context.

The life cycle approach allows to cover both the issues of critical raw materials supply for batteries manufacturing and the end-of-life management stage of the product with a closed loop approach. Different targets for collection of end-of-life batteries and recovery/recycling of materials are under definition and, together with the requirement to use secondary materials for the manufacturers and other labels and product's identification element, are able to give a relevant boost to the sustainability of the battery industry. CRMs are included in the regulation; thus, it will become clear to the stakeholders how to treat and recycle them if coming from end-of-life batteries.

1.2.7 Extended Producer Responsibility (EPR)

The Extended Producer Responsibility (EPR) is an environmental policy approach to extend the producer's responsibility of a product to the post-consumer stage of a product's life cycle. On this way the producers are responsible for the entire life cycle of the products that they introduce on the market, from their design until end of life (including waste collection and recycling). Indeed, the EPR scheme, introduced by the Waste Framework Directive 2008/98/EC, is defined as "a set of measures taken by Member States to ensure that producers of products bear financial responsibility or financial and organisational responsibility for the management of the waste stage of a product's life cycle".

Main key figures directly affected by the strategy are the producers, which are engaged to prevent wastes at the source, promote environment friendly product design and support material recycling management goals. However, even if the legislation lacks clarity on this aspect, all the value chain's stakeholders are involved: importers, collectors and recyclers, municipalities, consumers, and the producer responsibility organizations (PROs[21]).

In Europe, the Waste Directive is the main legislative reference which provides a broad legal framework for waste management activities and defines the basic concepts and principles for the sector. Other directives also require the mandatory application of the EPR scheme for specific products, such as packaging waste (Directive 94/62/EC), WEEE (Directive 2012/19/EU), batteries (Directive 2006/66/EC) and ELV (Directive 2000/53/EC). Considering the main objective to reduce the waste production from end-of-life products, otherwise enhancing the reuse of product at post-consumer stage, as well as recovery and recycling processes, the above-mentioned directives set specific European targets for the collection and the recycling for each specific product. The EPR system contributes to reach these goals.

Measures required by the EPR policy could be different country by country and product by product, proposing e.g., take back of the product or recycling fee in advance, collective/individual or financial/organizational schemes. The figure below reports main EPR systems applied to 6 product categories (vehicles, oils, packaging, paper, battery, WEEE) in several EU countries[22]:

[21] PRO: collective entity set up by producers or through legislation, which becomes responsible for meeting the recovery and recycling obligations of the individual producers.
[22] Development of Guidance on Extended Producer Responsibility (EPR) - Final report, European Commission – DG Environment, 2014

Main system						
Financial responsibility	AT FI NL SK SE	FI IT PT ES BE[6]	BE – c&i UK		BE[7]	
Financial responsibility through contracting with municipalities		BE[8]	CZ FR NL	FR		
Financial Responsibility with partial organisational responsibility			BE – hh	FI	AT BE[9] DK FR NL CH	DK – hh IE SE UK
Financial Responsibility with full organisational responsibility	DE		AT DE	SE		DK – c&i FI FR – hh LV

Figure 8: Type of producer's responsibility for 6 product categories.

Overall, several differences in the national law transposition are detected among the European countries for the different policy schemes and mandatory directives to which refer to. On this document, three countries have been taken into consideration for the EPR application on batteries and vehicles, considering last available reports on the topic:

Netherlands

Batteries[23]: collective scheme with single producer responsibility organization (Stichting batterijen)

In the EPR strategy industrial, automotive and portable batteries are distinguished. Industrial batteries do not have explicit collection or recycling targets, but producers are still required to take back their products, in the form of a business-to-business waste stream waste; traction batteries for electric and hybrid-electric vehicles are also included.

[23] EXTENDED PRODUCER RESPONSIBILITY CASE STUDIES ON BATTERIES, END-OF-LIFE VEHICLES AND MEDICINE IN THE NETHERLANDS, PBL Netherlands Environmental Assessment Agency, CPB Netherlands Bureau for Economic Policy Analysis, July 2021

Automotive batteries, used for the starting, lighting and ignition of all motor vehicles, are highly recyclable, up to 99% for lead-acid ones. Because of their positive market value, due to the metals content, they are usually not littered, landfilled or incinerated. Lithium batteries are more problematic with recycling rates of around 50%, however, larger batteries can sometimes be reused in stationary applications. Overall collection rate is set at 87%, which could be increased even more with the introduction of direct incentives for the consumers to dispose of waste separately.

<u>Vehicles</u>: collective EPR scheme with a single PRO (Auto recycling Nederland, ARN) for collection and treatment of ELV, relying on two instruments: take-back requirement and advance recycling fee

The take-back requirement considers two targets: reuse and recycling; reuse, recycling and recovery, where recovery means energy recovery via incineration. The advance recycling fee is paid at the time of purchase of a passenger car or light commercial vehicle. The combined target for reuse and recycling is currently 85% based on the weight of the vehicle. For the electric vehicles, lithium-ion batteries represent a challenge as above mentioned; if collection and reuse rate have seen a positive trend, the recycling step is still problematic. On this case, the EPR scheme helps to manage and treat the potential hazardous materials from ELVs (e.g. batteries, tires, fluids, airbags and LPG tanks) from one side, and to readdress to the market other low value materials, such as plastics or glass, from the other side. To point out the lack of incentives for the reuse of some ELVs materials. Higher recycling rate could be finally reached through the setting of a policy mix and introduce mandatory EPR also for motorcycles, scooters and heavy-duty vehicles.

From this example, some few recommendations can be done in relation to the stakeholders involved within the overall collection and recycling process. **For the citizens**, easy access to collection points is a key for high separate collection rate. Thus, policy should enhance number and distribution of collection points to cover the entire territory, while public awareness campaigns could be also complementary to the collection points supply to have an effective disposal and collection of end-of-life products. **By the side of the manufacturers,** realistic targets are needed to drive the process, considering reachable results and the context of real implementation; it would be important to increase the responsibility also for the share of products that are not separately collected.

United Kingdom

Batteries[24]: compliance EPR scheme; in total 5 PROs for batteries in 2019

The competitive EPR scheme was able to reach the EU collection target of 45% in a few years since its application in 2010. However, the competition among the PROs does not encourage the increase in collection rates, because they tend to maintain low prices for the customers. Also in the UK, the batteries collection is affected by the lack of clarity in terms of portable and industrial batteries distinction. The sparked mechanism is a high collection of lead-acid batteries, which are highly present in the market, cheaper and easier to recycle. For this and lack of policy incentives, the companies are not interested to increase their efforts in the collection of the other type of batteries unless the portables one. Other considerations in the UK EPR system are the competition for access to waste, which leads to high operational risks for the PROs, and a lack in the communication program to increase the users' awareness.

Switzerland

Batteries: a single private organization has been named to coordinate the national batteries collection (INOBAT Batterierecycling Schweiz)

The system allows to reach very high collection rate to reach, up to 60% for all waste batteries, despite high costs for producers. Potential drivers for this high rate are the dense collection network, the economic incentives provided for the collection points and the large expenses for awareness creation for the correct disposal of batteries among the population.

From the EPR scheme analysis, follow these general considerations at EU level legislation:

EU ELVs Directive: missing vehicles

One problem identified in the EU ELVs Directive is the track of all EoL motor vehicles. Every year around 60% of the ELVs treated seems to be deregistered and so illegally dismantled and/or exported to third country. This lead economic and environmental damages. The ELVs Directive should take measures to overcome this problem.

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[24] Analysis of Extended Producer Responsibility Schemes – Report, Adelphi consult GmbH, June 2021.

Co-ordinated action at the EU level for the environmental responsibility of the used vehicles exported abroad

EPR schemes do not cover the ELV treatment to third countries, thus do not follow the ELVs in other countries where are used but cover only in the country's burden where the EPR is set up. This is a lack in the overall value chain, meaning the necessity to improve the EPR policy in more countries and working jointly with all the actors involved and directive framework. Waste shipment and waste directive are also relevant for this implementation. The PROs are identified to have an important role in the general process of implementation.

Lack of clarity regarding batteries subject to system participation

The EU Battery Directive does not distinguish between portable and industrial batteries. According to the Battery Directive, portable batteries are button cells, battery packs or accumulators that are sealed, can be carried by hand and are not intended for industrial or automotive use. This is a shortcoming in the directive which does not allow covering all the batteries with due importance and environmental relevance; a threshold would be helpful to improve both types of batteries collection, as proposed by the UK regulation.

The EPR scheme is a powerful policy strategy to manage the end-of-life of products, shifting the financial burden of collecting and treating end-of-life products from taxpayers to producers. Benefits of its application drop on environmental and economic aspects, based on scheme design and the mix of instruments used, specific for each country.

The EPR scheme was shown to be effective in the collection and recycling targets achievement set by the single products' EU directives. Nevertheless, it suffers from different factors, such as the market fluctuation of sales and disposal of EoL products, as well as realistic targets and system of counting, which does not always give realistic and inclusive data of all products. It is also a complex policy scheme, which involves several actors in the operational deployment, and relies on different regulations from the legislative point of view. As mentioned earlier, the EU Batteries does not differentiate between portable and industrial batteries, nor do the national EPR schemes. As a consequence, there is no monitoring on collection, and subsequential recovery and recycling of the batteries. Linked to this, the ELVs system seems to reach high recycling rate, although it is reported the missing of a relevant percentage of cars which disappear in the illegal dismantling system; in addition, not all motor vehicles are included either in the EU ELVs Directive, or in the national EPR schemes, which indeed represents an important market segment to be covered. Hybrid and electric vehicles are new products, which are starting to be considered by the policy. Some incentives are also proposed for the recovery of some materials from ELVs, e.g. plastics or glass. No incentives or specific considerations have been made for the CRMs, even if they are included in the components collection of batteries and vehicles as products.

As a conclusion, the EPR scheme still needs to be implemented to cover better all the products, which have been already in the market for years (automotive and industrial batteries), or are entering it (industrial batteries, electric vehicles). More specific measures should be made for the CRMs, considering their environmental and strategic importance at the European level. The application of the EPR scheme should reflect the complexity of the regulation framework covering the topic of end-of-life products, including the Eco-Design directive, Batteries and ELVs directives, but also waste and waste shipment directives.

1.3 Extra-EU regulatory assessment related to how to treat End-of-Life rare/not-rare materials contained in FCH technologies

In this section the summaries of the information gathered through interviews and contacts with members of the Advisory Board from the USA, Japan, Korea, and Singapore are reported. The latter were asked about current situation in terms of diffusion of hydrogen technologies in their Countries plus any information about current practices in disposal and regulatory and standardisation approaches in terms of eco-design and recycling.

1.3.1 USA

For the US, HRD America provided the project with information on current market and approaches to recycling. Hydrogen-fueled vehicles sales/leases are mostly concentrated in California where a few hydrogen fueling stations already exist. Stations are being planned or built in the Northeast and Hawaii, and fuel cell transit buses are already operating in cities like Boston, Massachusetts, and Flint, Michigan. There are plans to expand FCV offerings over the next few years as infrastructure grows and the technology continues to mature.

From a regulatory and standardization point of view, the DOE Energy Efficiency and Renewable Energy Office's Hydrogen, Fuel Cells & Infrastructure Technologies Program is trying to coordinate a few activities, which involve many stakeholders. Alongside testing and safety of fuel tanks and refuelling hydrogen stations, the Society of Automotive Engineers (SAE) is active on aspects related to eco-design. Its Recycling Subcommittee has the mission of developing a recommended practice document that incorporates existing recycling practices and identifies technical and environmental sustainability issues and applies them to the design of the proton exchange membrane (PEM) fuel cell (FC) systems. The Recommended Practice to Design for Recycling Proton Exchange Membrane (PEM) Fuel Cell Systems (STABILIZED Sep 2011) (J2594_202301) document was confirmed at the beginning of 2023.

In terms of disposal, a study conducted by Strategic Analysis Inc. for the US Department of Energy on Fuel Cell System Analysis[25] reveals that activities already exist in the recycling of fuel cells elements, in particular:

1. for the MEA: maximum efforts are concentrated on the recovery of Pt, with many patented methods (see below Fig. 8 and 9 for an example)
2. Ionomer: far too degraded at end of life, however the recovery of fluorine is seen as a potential business opportunity;
3. Bipolar plates and coatings: materials such as stainless steel (higher volumes), but also gold and ruthenium coating and also titanium and titanium oxide;
4. For the Balance of Plant Components: they are similar to systems for other motor vehicles, hence the recycling approach and infrastructure are the same.

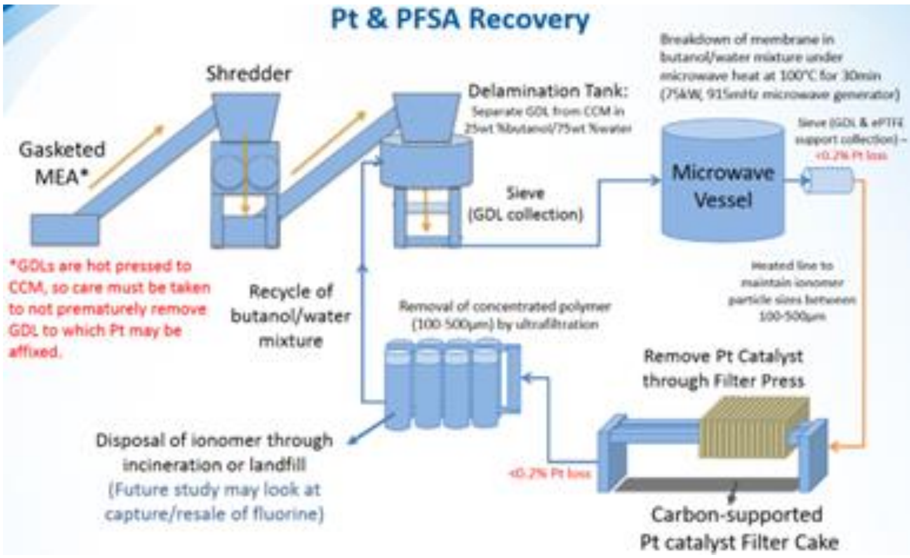

Figure 9: Process of PT and PFSA recovery based on US Patent US 8124261 B2 (BASF) 2012.

[25] https://www.hydrogen.energy.gov/pdfs/review19/fc163_james_2019_o.pdf

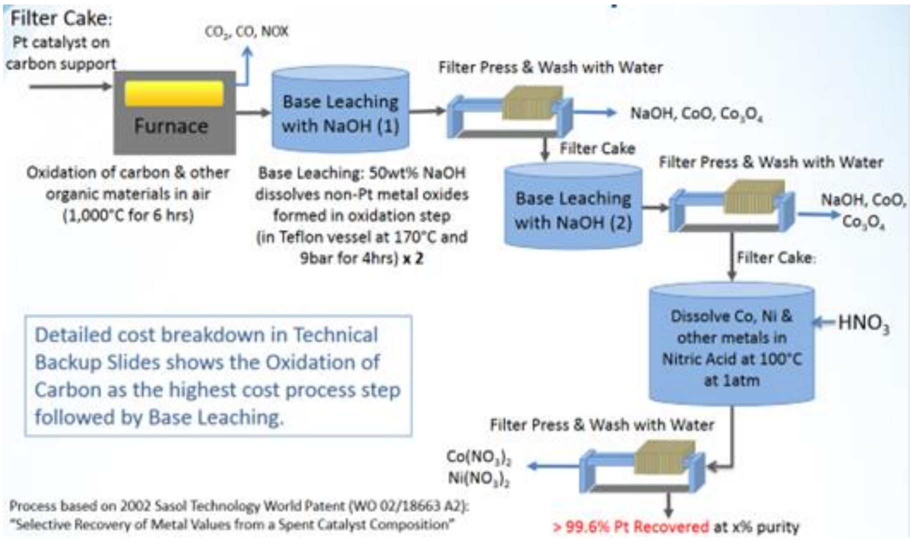

Figure 10: Process of Pt and PFSA recovery based on 2022 Sasol technology World Patent WO 01/18663 A2.

Overall, while there are complexities in the processing of some parts, which need to be separated for specific treatment, it is expected that the existing motor vehicle recycling infrastructure could deal with these systems also. However, an ideal development of the recycling process is to streamline it so that it can handle different stack designs.

A process flow on the collection and treatment of fuel cells from vehicles is also reported in the same document – see Fig. 10. This flow implicitly confirms the expectation that hydrogen-fuelled cars will follow the same pathway for disposal as any other end of life vehicles

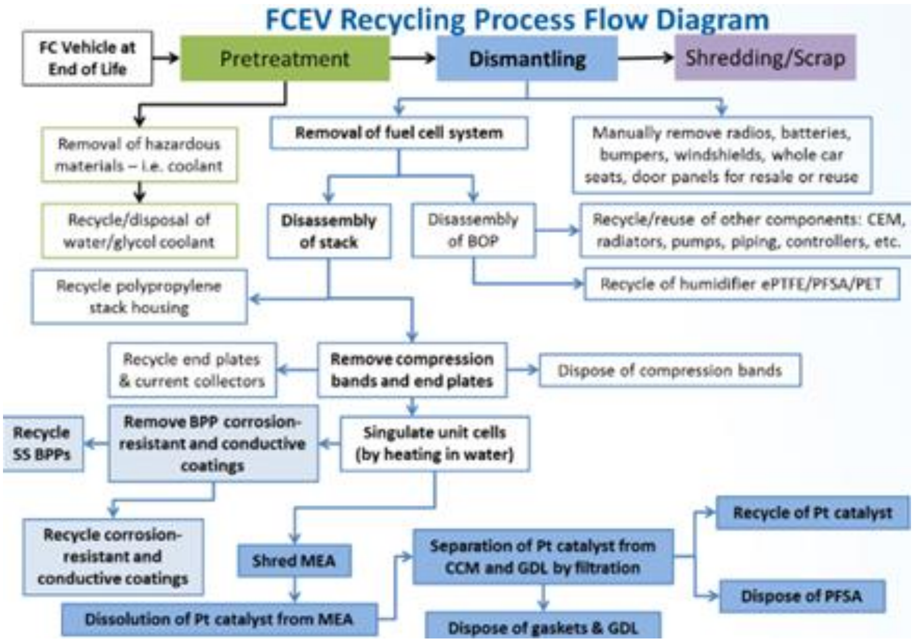

Figure 11: Recycling process flow diagram.

1.3.2 Japan

1.3.2.1 General approach of TOYOTA company

TOYOTA Europe gives us a Japan vision. In 1998, Toyota was the first in the auto industry to introduce ISO14001[26] in its design and development area. Since then, it has been assessing recyclability in advance, at the vehicle development stage. From 2005, Toyota introduced the "Eco-VAS"[27] a comprehensive environmental assessment system, which is based on the approach of LCA (Life Cycle Assessment), through the entire vehicle development process. Assuming the occurrence of end-of-life FCVs in the future, Toyota started considering the operation procedures and construction methods of dismantling a few years prior to sales launch.

Through the Eco-VAS, Toyota is able to take into account both environmental performances (e.g. reduction of exhaust gas, noise, fuel economy improvement) and technical needs (e.g. customer needs, cost) in each life cycle stage. Main efforts can be detected in the introduction of technologies and procedures for an easy dismantling of end-of-life vehicles, for the recovery and recycling of its components (recycling 100% of rare metal tungsten), as well as reduction of resources and improvement of secondary materials use. The LCA approach covers both the recovery & recycling technologies and the system's organisation. Their approach in the vehicles' recovery process can be summarised as follows:

- Direct collaborations with dismantling – and recycling – companies, coupled with an eco-design strategy;
- Dealer support parts distribution partnerships are established between Toyota and local dealers;
- Creation of partnerships for the recovery of materials;
- Implementation of the production plant performance – reducing waste and resources;
- Increasing the awareness for the recovery of materials on the end-users.

[26] The international standard for environmental management systems
[27] Eco-Vehicle Assessment System

1.3.2.2 Proper treatment for HV and FCV: the MIRAI case

MIRAI is a zero-emission vehicle with both FC stack and HV battery. Toyota group promotes a sustainable and low-impact end-of-life management of HV batteries, acting on a safe removal methodology, collection system planning and a final proper treatment process **Toyota takes care of the FC stack's recovery and recycling in Fuel-Cell Vehicle too.** The vehicle has two tanks of carbon fibre reinforced plastic (CFRP) that store high-pressure hydrogen gas at 70 MPa of pressure. The group studied the disposal of the remaining hydrogen gas in the tank, the removal and recovery of HV battery and FC stack. Interesting, the pilot program on MIRAI was conducted in Europe, where a first collection and recycling system was established. A proper recycling of end-of-life hydrogen tanks was conducted at local level with recycle of materials, such as CFRP, and exploration for FC recycling conducted: chemical reaction by hydrogen gas supplied from the hydrogen tank and oxygen in the air taken from outside the vehicle.

Dismantling of FCV is also a priority topic to solve before launching the product. On this sense, Toyota started to study the operation procedures and also provided a dismantling demonstration for the Japan ELV Recycle Association in view of Article 3 of the Automobile Recycling Law: "Provide Information of Automobile Structure".

Figure 12 shows the steps of the FCV dismantling operation in Toyota:

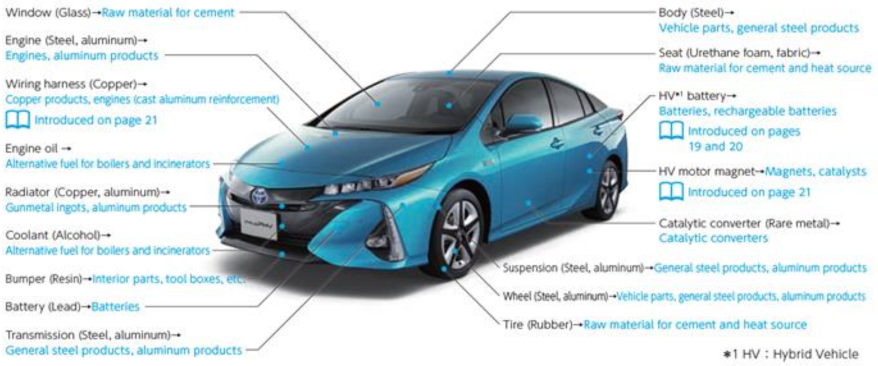

Figure 12: Steps of the FCV dismantling operation.

Specific efforts are also made on the recycling/reuse of rare metals and rare earths materials, as one of the main factors with major impact on the vehicles production and sales in the future. To overcome the risks associated to the rare metals use, Toyota has advanced measures like the recycle resources from urban mining, the research for alternative materials, as well as the reduction of materials' quantities, and the stabilisation procurement by opening new routes. Already in 2010, Toyota reached the "battery-to-battery" recycling operation in partnership with other companies. End-of-life NiMH batteries removed from hybrid vehicles remanufactured and reused for stationary rechargeable batteries and as supply batteries for vehicles.

Clean Hydrogen Partnership
Co-funded by the European Union

The interest of Toyota in a more sustainable vehicles production and final recycling has led to the establishment of an Automobile Recycle Technical Center for the research on recycling and dismantling technologies.

1.3.2.3 Japanese hydrogen strategy and regulatory framework

Japan is an extremely high industrialised country whereby hydrogen is one of the key energy sources, improving the industrial competitiveness and assuring a green and sustainable growth at the same time. Indeed, Japan is a global leader in fuel cell technology, especially fuel cell vehicles (FCVs). Considering the context, hydrogen and carbon neutrality strategies are here reported:

- **Basic Hydrogen Strategy**[28] (2017): The Basic Hydrogen Strategy seeks to realize a hydrogen-based society on a step-by-step basis under the following three-phase program, considering both short and long periods of time required to overcome technological challenges and secure economic efficiency: (i) Phase 1: Dramatic expansion of hydrogen use (from present); (ii) Phase 2: Full-fledged introduction of hydrogen power generation and establishment of a large-scale hydrogen supply system (by the second half of the 2020s); (iii) Phase 3: Establishment of a CO2-free hydrogen supply system on a total basis (by around 2040).
- **Green Growth Strategy Through Achieving Carbon Neutrality in 2050**[29] (2020): This strategy is an industrial policy to lead the challenging goal of achieving carbon neutrality by 2050 toward a positive cycle of economic growth and environmental protection. Upholding high goals for each of the 14 priority fields, this Green Growth Strategy makes explicit current challenges and future actions by priority field and formulates action plans covering comprehensive policies in areas such as budgets, taxes, regulation reforms and standardization, and international collaboration.
- **Strategic Roadmap for Hydrogen and Fuel Cells (2014, 2016, 2019):** the roadmap got more updates in the last years. Last of them was in 2019, where the government set new targets on the specifications of basic technologies and cost breakdowns and defined measures that are needed to achieve these targets. For example, the mobility targets included 200,000 FCVs by 2025 and 800,000 by 2030, as well as 320 fuelling

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[28] https://policy.asiapacificenergy.org/node/3698
[29] https://www.meti.go.jp/english/press/2020/1225_001.html

stations by 2025 and 900 by 2030[30]. The development and implementation of the hydrogen supply chain is also one of the major points of the strategy.

Under this legal framework, companies, such as Toyota are involved and encouraged to participate in the development of a hydrogen economy. The recycling technologies and life cycle approach in the vehicles manufacturing are in line with the following regulations and standards:

- **The Automotive Recycling Law**: effective since 2005, it mandates appropriate roles and responsibilities between automobile manufacturers and other involved parties, to promote the recycling and proper treatment of end-of-life vehicles. Under the Automobile Recycling Law, Toyota collects CFC/HFC, airbags and ASR from end-of-life vehicles, and actively promote recycling or proper treatment.

30 https://www.csis.org/analysis/japans-hydrogen-industrial-strategy

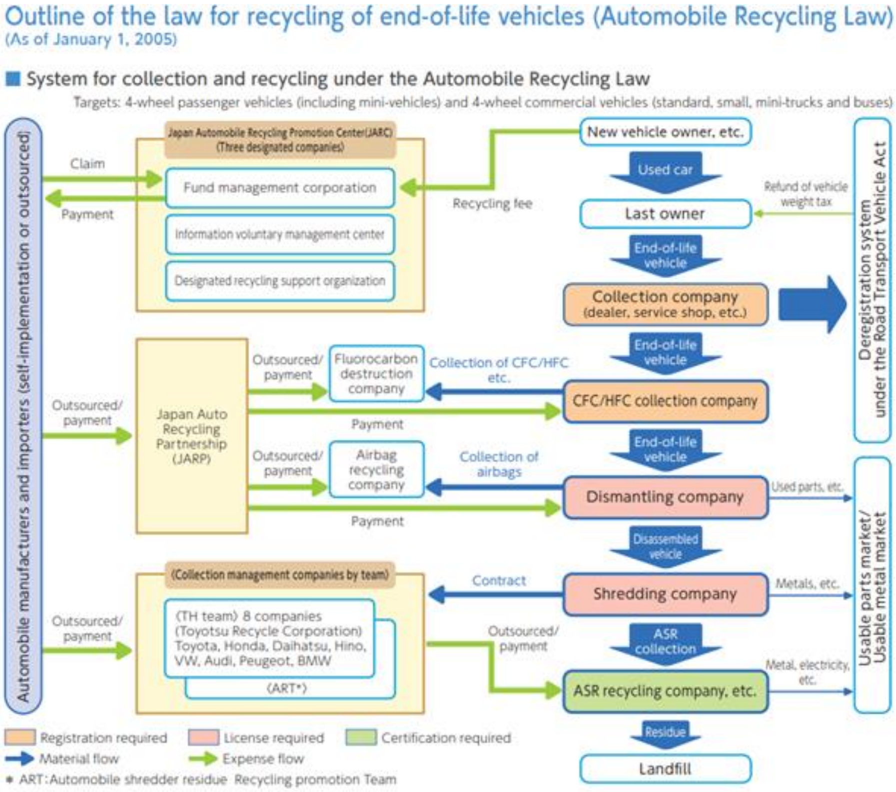

Figure 13: System for collection and recycling under the Automobile Recycling Law.

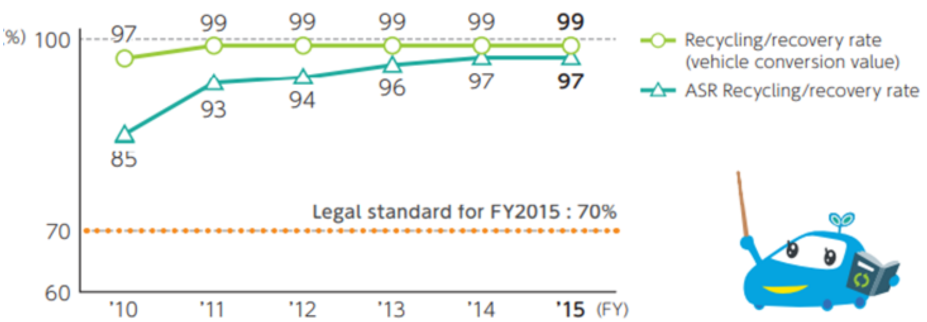

Figure 14: Transition in Toyota's recycling/recovery rate and ASR (Automotive Shredding Residues) recycling/recovery rate.

- **Fuel Cell Japanese Industrial Standard (JIS):** the Japanese Industrial Standard Committee is currently directly involved with hydrogen technology related standard developed at international level by the International Electrotechnical Commission (IEC). Japan, as pioneer in the fuel cell and hydrogen technologies, is guiding the discussion in the IEC/TC105 for the developing of international standards for fuel cell technologies and their applications (see section 3.5.1). The JIS is actively part of the WG4: Stationary fuel cell performance and WG11: Single-cell test methods. These working groups are related with performance and safety issues.

The complete Japanese regulatory framework is partially unknown due to difficulties of information access and the language; specifically on the circularity and recycling in FCH technologies, only the Automobile Recycling Law has been identified. It is not clear how much the legislation covers the recycling issues, although it seems to be a high-interest factor, seen the efforts of Toyota Group, also influencing companies at national level.

1.3.3 Korea

A brief call with Dr Tim Ho Shin of the Energy Efficient Materials Centre – Korea Institute of Ceramic Engineering and Technology, highlighted the following points with respect to the Korean market.

Korea is planning the development of about 800MW H_2- based power generation in the next few years, of which 70% based on PEM fuel cells. PEM fuel cells are mostly used for mobility, with Hyundai planning the sale of about one hundred thousand vehicles.

In 2020, Hyundai established the world's first mass-production system for hydrogen electric trucks and it exported 47 XCIENT Fuel Cell heavy-duty trucks to twenty-three clients in Switzerland from 2020 to June 2022. The trucks supplied to Switzerland have collectively driven more than 5.7 million kilometres as of January 2023, proving the product's reliability and eco-friendliness.

Hyundai Motor also signed an agreement to supply 27 XCIENT Fuel Cell trucks to seven German companies in connection with the German Federal Ministry for Digital Transport (BMDV)'s funding program for eco-friendly commercial vehicles in August 2022.

Several trials are ongoing also in the US, while cooperation with other Countries is being actively sought by the company for the trial and consequent introduction of the hydrogen fuelled trucks.

Hyundai is looking at the whole hydrogen supply chain, pursuing hydrogen-related business opportunities from production through reforming and carbon capture, use and storage (CCUS), to hydrogen storage, transportation and utilisation. The Group focuses on a 'Waste-to-energy' hydrogen production system based on biogas extracted from organic waste.

Neither eco-design nor recycling is among the issues to be tackled in the short term, as the company is mostly concentrating on the stability and efficiency of the cells for their vehicles. However, the cost of platinum is a critical point, and this could be a driver.

Korea's 2007 Act for Resource Recycling of Electrical and Electronic Equipment and Vehicles (referred to as RoHS) is the legislation of reference for what concerns the treatment of electric and electronic waste, the restriction of hazardous substances use and disposal of end-of-life vehicles up to a certain weight. It creates a framework to hold producers and importers responsible for their use of resources. The law addresses the use of hazardous substances, recyclability of materials, collection of ELVs, recycling rates, and information exchange through an on-line database. In other words, the Act compounds the EU directives on RoHS, WEEE and ELV. With respect to ELV, the Act sets a mandatory target recycling rate of 95% including 10% energy recovery as a maximum. The ELV enters a chain of processing facilities described in Fig. 15.

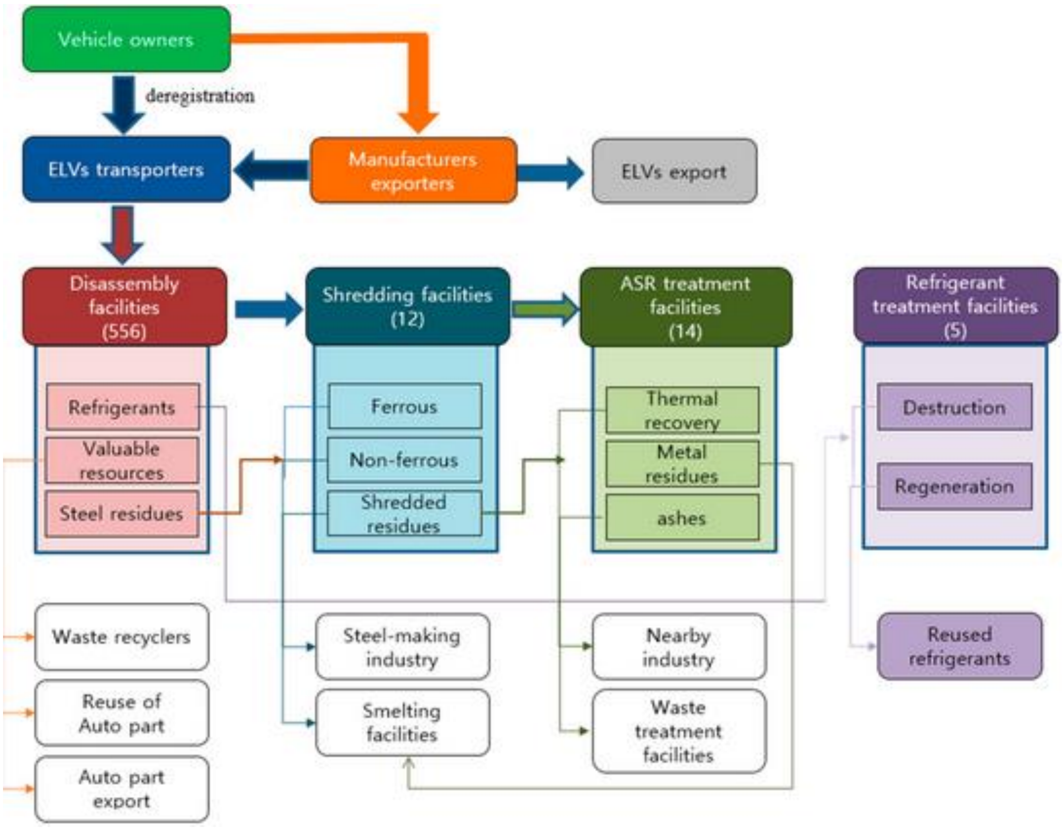

Figure 15: ELV chain.

It is expected that any fuel cell based ELV would enter the same chain of treatment, with specialist recyclers dealing with the hydrogen systems.

1.3.4 Singapore

A discussion on the Singapore situation with respect to the hydrogen market, eco-design and recycling was conducted with prof. Chan Siew Hwa from Energy Research Institute at NTU (Nanyang Technological University Singapore).

The vehicles market in Singapore is conditioned by the regulation imposing the acquisition of a very costly government certificate that allows citizens to buy a vehicle. For this reason, cars are kept in operation for an exceptionally long time, after which they are exported.

Singapore relies for much of its vehicles' production and disposal facilities on China (buses and taxis) and other major Asian players (Japan and Korea for passenger vehicles). However, research is ongoing on recycling of batteries and fuel cell systems. With respect to SOFC, a study conducted by the Institute achieved a rate of 88% recycling.

Looking at what is known for the Chinese approach, eco-design is not a concern yet, as industry is concentrating on bringing down the cost of the power system also through economies of scale. Raw materials are not necessarily a concern being the Country rich in the elements required for the production of SOFCs.

2 Standardization Assessment

The EU is planning advanced fuel cell and hydrogen technology deployments that will decarbonize the electricity and transportation sectors in the near future. The plan is to use the anticipated surplus of renewable energy sources to generate significant volumes of green hydrogen (adopted laws aim for 65% of power from renewable sources by 2050).

However, at the recycling and decommissioning stages, the anticipated commercial FCH technology is not yet prepared for broad deployment.

This section provides a brief overview of the fuel cell and hydrogen (FCH) technology, documentation, and research on current and emerging techniques and technologies, as well as relevant standards.

As the FCH nears the end of its useful life, numerous electrical and electronic components inside must be properly taken care of. These parts are handled as WEEE and are categorized as EEE (Electrical and Electronic Equipment) (Waste Electrical and Electronic Equipment).

WEEE is a mixture of (possibly hazardous) materials and components that, if not managed appropriately, might cause major environmental and health issues. Therefore, it is crucial to improve used electronic equipment collection, treatment, and recycling in order to enhance WEEE environmental management, promote a circular economy, and boost resource efficiency.

Regarding End of Life of electrical components, the following two recommendations should be made:

The **WEEE Directive**, also known as Directive 2002/96/EC (8), became effective in February 2003. To address the rapidly expanding waste stream, the European Commission recommended changes to the Directive in December 2008. The new WEEE Directive 2012/19/EU becomes effective on August 13, 2012, and on February 14, 2014. With the addition of a PV that will take effect right away, the new Directive's goals are the same as those of Directive 2002/96/EC.

All EEE, with the exception of those expressly prohibited, are covered by the WEEE Directive as of August 15, 2018. The WEEE Directive promotes collaboration between recyclers and producers to make it easier to reuse, disassemble, and recycle WEEE. The major aims of the WEEE Directive can be accomplished thanks to eco-design.

The WEEE Directive places the burden of proving conformity on the producers of electric and electronic equipment by establishing recycling and recovery targets for specific categories of domestic and commercial electrical and electronic devices. The objectives outlined in this directive call for a range of recycling rates of parts and materials of 50% to 80% by weight and a recovery rate of 70% to 80%, including materials burned to produce energy.

The **RoHS-I Directive** on the Restriction of the Use of Hazardous Substances in Electrical and Electronic Equipment, Directive 2002/95/EG. The RoHS II Directive (2011/65/EU), which was passed on July 21, 2011, and came into effect on January 2, 2013, is an update to the original RoHS Directive. It has an improved regulatory structure and greater legal certitude but nevertheless covers the same chemicals as the original Directive. The progressive development needs to include additional electronic and electrical equipment, cables, and spare parts require periodic appraisal.

2.1 PEMFC Technical overview

A polymer electrolyte membrane (PEM) and two electrodes with added catalyst layers make up a PEMFC's major parts. A PEM serves as an electrical isolator and separator between the two electrodes, known as anode and cathode. Protons can pass through the PEM while reactant gases are blocked. The membrane electrode assembly is the name given to these three parts when they are used together (MEA). A hydrogen oxidation reaction (HOR) on the anode side separates protons from electrons. The protons travel through PEM to the anode side of the fuel cell, and the separated electrons travel through an external electronic conduction circuit to an electrical load, where the fuel cell's generated power is used.

Protons and electrons combine with oxygen during the oxygen reduction process (ORR) on the cathode side to generate water. At the triple-phase boundary, where the electrolyte, catalyst, and reactants are all in contact, the most significant electrochemical reactions take place.

Bipolar plates' embedded flow field channels allow gas to flow across them. Bipolar plates, which are positioned on either side of the MEA, serve as current collectors, gas distributors, and mechanical support. . Graphite, graphite composites, or stainless steel materials are typically used to make bipolar plates. Typically, carbon paper or cloth serves as the electrode's gas diffusion layer (GDL), while platinum or platinum alloy catalyst is used as the catalytic layer and is supported by carbonaceous material. PEMs are created from sulfonated polymers that are hydrophilic and strongly proton-conducting (when saturated with liquid water).

The most widely used PEMs on the market today, including DuPont's Nafion, are constructed of perfluoro sulfonic acid (PFSA). Sulfonated polyetheretherketone (s-PEEK) and polystyrene sulfonic acid (PSSA) have recently been employed as less expensive substitutes, nevertheless. Other varieties can also be used, including those based on zirconium phosphate.

Table 2: PEMFC components and materials.

Component	Material
Bipolar plates	*Graphite / Graphite Composites* *Stainless Steel Materials*
Gas Diffusion Layer (GDL)	*Carbon Fibre Paper / Carbon Cloth*
Catalyst Layer	*Pt / Pt-Alloy*
Polymer Electrolyte Membrane	*PFSA / s-PEEK / PSSA / Zr Salts*

2.2 SOFC Technical Overview

The excellent power generation capabilities of solid oxide fuel cells (SOFCs), which claim sufficient electrical efficiency for household appliances and autos, are drawing increasing amounts of interest. A solid oxide electrolyte separates the cathode from the anode in a single fuel cell. The cathode side receives an oxidant continually, whereas the anode side receives fuel continuously. In conventional systems, the oxygen molecules are broken apart and the oxygen atoms are ionised (reduced) on the cathode side. The oxygen ions are then conducted through oxygen ion conducting electrolyte membrane to the anode side, where they recombine with molecular hydrogen to form water and excess electrons. These electrons are transferred back to the cathode via external electrically conducting circuit and the electric load, which is inserted into the circuit, consumes the produced electric power.

Most electrolytes are made of ceramic materials that can conduct ions and are located between a cathode and anode terminal. Commonly, it could be a conducting medium for oxide ions (O2-), however lately also proton (H+) conducting electrolytes are being explored. Yttria-stabilized zirconia (YSZ), a ceramic substance, is frequently utilized in SOFCs as a solid electrolyte material. Scandia-stabilized zirconia (ScSZ), an alternative material, has demonstrated greater conductivity and stability when compared to YSZ. Scandia is a useful material for SOFC electrolyte use; however its cost and availability are the main drawbacks. Another intriguing solid electrolyte material is cerium gadolinium oxide (CGO), also known as gadolinium doped cerium (GDC), which exhibits greater conductivity at low temperatures than YSZ or ScSZ.

Table 3: SOFC components and materials.

Component	Material
Cathode	*Lanthanum Strontium Cobaltite (LSC)*
Electrolyte Layer	*YSZ / ScSZ / CGO / GDC*
Anode	*Ni:YSZ*
Support Layer	*Ni / Ni:YSZ*

2.3 Critical Raw Materials

A criticality approach is one that considers the hazards involved in the creation, utilization, or end-of-life management of a raw material. A raw material is considered critical when:

- It is utilized in industries that are considered strategic for the government or the economy (transports, energy, defence, and electronics);
- It is difficult to substitute in the near future;
- Its reserves and production are regionally concentrated;
- It has a wide range of industrial applications with significant economic value.

Criticality is not a universally accepted concept. As it truly refers to four degrees of risk - geological, economic, strategically available, and environmental - the criticality of a raw material might differ from one nation to the next.

FC and hydrogen storage technology production requires about 30 raw materials.

Critical materials assessments are still in their early stages, there is room for improvement in the evaluation procedures, and new sectors and areas require research on crucial materials.

There are currently a number of publications and research that propose and/or evaluate various methods for determining material criticality.[31]

According to the 2023 European Critical Raw Materials Act[32], certain of these materials (shown in bold in the table below, listing raw materials considered critical and strategic) are deemed to be extremely important for the EU economy:

Critical Raw Material	Strategic Raw Material
Antimony	
Arsenic	
Bauxite	
Baryte	

31 Criticality and Life-Cycle Assessment of Materials Used in Fuel-Cell and Hydrogen Technologies
32 European Critical Raw Materials Act, European Commission.

Critical Raw Material	**Strategic Raw Material**
Beryllium	
Bismuth	*Bismuth*
Boron	*Boron - Metallurgy grade*
Cobalt	*Cobalt*
Coking Coal	
Copper	*Copper*
Feldspar	
Fluorspar	
Gallium	*Gallium*
Germanium	*Germanium*
Hafnium	
Helium	
Heavy Rare Earth Elements	*Rare Earth Elements for magnets (Nd, Pr,*
Light Rare Earth Elements	*Tb, Dy, Gd, Sm, and Ce)*
Lithium	*Lithium - Battery grade*
Magnesium	*Magnesium - Metal*
Manganese	*Manganese - Battery grade*
Natural Graphite	*Natural Graphite - Battery grade*
Nickel – battery grade	
Niobium	
Phosphate rock	
Phosphorus	
Platinum Group Metals	*Platinum Group Metals*
Scandium	
Silicon metal	*Silicon metal*
Strontium	
Tantalum	
Titanium metal	*Titanium metal*
Tungsten	*Tungsten*
Vanadium	

More than half of the raw materials needed for FC technology's production come from a variety of sources, each of which has a meagre supply share of less than 7%. The largest provider of raw materials is China, with a share of more than 20%, followed by South Africa and Russia. South Africa accounts for the majority of the world's output of platinum (71%) and is followed by Russia (16%) and Zimbabwe (6%). Three major suppliers—Russia, South Africa, and Zimbabwe—also supply the majority of the other PGMs, including palladium, rhodium, and ruthenium.

The 13 processed materials listed below are the ones that are the most pertinent for FC and hydrogen storage/production technologies at the next stage of the supply chain. These materials include:

- Porous carbon ;
- Yttria stabilized zirconia;
- Lanthanum strontium compounds (i.e. doped with cobalt, iron, manganese, etc.)

- Polymers (e.g., perfluoro sulphonic acid - PFSA) ;
- Carbon fibre composites (CFC);
- Stainless steel;
- Graphene;
- Scrap and flake mica;
- Boron nitride powder;
- Nano materials & carbon nano tubes;
- Carbon cloth/paper;
- Polyamide ultramid;
- Metal hydrides.

Mesoporous carbon and carbon nanoparticles are two diverse types of carbon- or carbon-based-based-materials that have been produced for electrodes. European businesses provide about 25% of FC components and 40% of processed products.

In many different forms of FC, including PEM, DMFC, and PAFC stacks, gas diffusion layers (GDLs), which are essential parts, are frequently made of carbon fibre paper and carbon fabric (cloth). The PEMFC stack contains multipurpose components called bipolar plates (BPP).

Graphite and stainless steel are materials used to make bi-polar plates. To boost functionality and lifetime, stainless steel for bipolar plates must be coated. Gold and other noble metals are common examples of coating materials with great characteristics. Finding substitute coating materials is preferred because noble metals are expensive. Asia (particularly Japan and South Korea) and North America are the two regions that manufacture the most FCs (Canada and USA). The integration of the stack of assembled cell components into the finished system is the last stage in the FC supply chain. Crucial factors that can affect FC performance and reactant distribution in the cell stack include stack design and cell assembly. The contact behaviour of the bipolar plates with the membrane electrode assembly will also be impacted by the cell assembly (MEA).

2.3.1 Standardization on Critical Metals

167 national standards bodies from around the world are members of ISO[33], an independent, non-governmental international organization. Via its members, it brings

33 https://www.iso.org/what-we-do.html

specialists together to exchange knowledge and create voluntary, market-relevant international standards that foster innovation and offer answers to major problems.

Since its inception, ISO has been working on metal standardization. Therefore, in 1953, ISO/TC 79 "Light Metals" was established. The new subcommittees for titanium and magnesium were added to this committee. Afterwards, new committees such as ISO/TC 333 "Lithium" were established in 2021. The work primarily focuses on methods for chemical analysis, packaging, classification, and traceability. These techniques are employed in the resolution of commercial litigation and disputes. In fact, there are frequently disputes between suppliers and clients about the quality of the given metals and minerals. By offering a global reference method, the ISO standards on chemical analysis methodologies stabilize the market.

China has requested the establishment of three new ISO committees on metals and materials since 2015: lithium, rare earths, and gold, which have all failed. It should be highlighted that the newest ISO committees span a wide range of the industry, from metal recycling to mining. In the past, metallurgical issues were the main focus of ISO committees, which had a more limited reach. The presence of SAC is revealed through a review of the current ISO committees (Standards Administration of China). In order to stabilize the market and ensure the security of pertinent key supplies, it appears necessary to increase the participation of European stakeholders in ISO Technical Committees.

From the European perspective, the mining and metals sector plays a vital role in the EU economy and is crucial to many other sectors, including construction, automotive and electronics. With regard to the definition, classification, testing, analysis, and technical delivery requirements of the products of the metallurgical industry, the continuously rising demand for minerals necessitates a significant standardization effort. The technical committees of the Comité Européen de Normalisation (CEN) responsible for the standardization of metals are old, and no new committees have been established in many years. Given the size of this market on a global scale, international rather than European standardization seemed more acceptable.

In November 2022, AFNOR, the French Standardization Authority, suggested the establishment of a new Technical Committee at ISO to support the standardization of key metals and minerals.

This new ISO Technical committee's proposed mandate is as follows:

Standardization in the field of Speciality Metals and Minerals concentration, separation. The work program includes terminology, classification, technical conditions of delivery to overcome transport difficulties, unified testing and analysis methods to improve the overall quality of Speciality Metals and Minerals. Speciality Metals and Minerals covered by this technical committee are the following: ***Bismuth, Beryllium, Cobalt, Gallium, Graphite, Hafnium, Indium, Niobium, Palladium/platinoids, Rhenium, Silicium, Tantalium, Tungsten, Vanadium and Zirconium*** *(non-fixed list).*

Additional metals and minerals may be added if the extension of the scope is approved by ISO/Technical Management Board.

Excluded: Components, Products, Mining (which are already covered by others ISO Technical Committee).

Two categories of standards for specialty metals and minerals are planned by AFNOR: the first is for basic requirements (terminology, classification, packaging, marking, etc.), and the second is for requirements for testing and analysis procedures (sampling, requirements and analytical procedures for specialty metals and minerals, chemical analysis, etc.).

Focusing on Italian legislation and standardization, MiSE and Mite have signed the inter-ministerial decree that formalizes the technical table "Critical Raw Materials" (CRM). The CRM table is made up of organizations, research centres, supply chain consortiums, and trade associations, and its goals are to improve coordination and formulate suggestions useful for the creation of regulatory conditions, economic conditions, and market conditions intended to ensure a secure and sustainable supply.

The table is composed of 4 working groups:

Working Group 1 - "Requirement Analysis", coordinated by Confindustria, is in charge of estimating the demand for crucial raw materials in the future;

Working Group 2 - "Mining," which is coordinated by ISPRA, seeks to identify the potential for primary and secondary mining activities (recovery from mining waste) by examining the prospects for sustainable mining in Italy, including the recovery of raw materials from abandoned sites and from mining waste;

Working Group 3 on Ecodesign is being coordinated by ENEA and intends to examine how eco-design may be used to lessen the demand for essential raw materials.

With a focus on WEEE, the main goal of **Working Group 4** "Urban Mining," coordinated by ENEA, is to estimate the potential of urban mining activities. Following an analysis of best practices at the European and global levels, the group will also develop regulatory proposals for simplification.

2.4 EoL Technologies

PGMs like platinum, iridium, and ruthenium are frequently chosen as the targets of EoL technologies for FCH products due to their economic importance. For instance, due to the high price of PGMs , electrodes are a major contributor to the PEM-based stacks' comparatively prohibitive costs, despite the relatively low weight of such precious materials (around 50g in an automotive stack). In this context, typical approaches for the recovery of PGMs include hydrometallurgical and pyro-hydrometallurgical techniques. The effectiveness of the recovery process and the initial concentration of precious metals, however, determine their economic viability.

The recovery of PGM catalysts from PEM stacks is another goal of modern EoL methods, which frequently also enable the recovery of other pertinent components like the ionomer and the carbon support.

Ni and Ni composites cannot be disposed of in landfills, and any handling operation must have dependable procedures to manage them properly. Due to the ubiquitous usage of nickel in numerous products, there are numerous hydrothermal and hydrometallurgical recovery processes for this substance. Another popular technique for the recovery of YSZ in SOFC stacks is hydrothermal treatment. Despite the potential advantages of recovering lanthanum-based elements for this type of stack, there is no standard EoL technology available for their recycling with a reasonable purity.

Another crucial waste stream in the EoL of SOFCs is ceramic materials (YSZ, LSM). The relatively moderate material value of these ceramics (around 86 $/kg for YSZ and a little more for LSM at the beginning of 2023), and the significant energy requirements associated with processing them, currently work against recycling this waste stream. Yttrium and Lanthanum are strategic materials, since they fall in the REES category, and have a wide variety of other application outside of FCH technologies, hence they could possibly be reused to make catalysts, superconductors, garnets and as material enhancers.

2.4.1 Hydrometallurgical treatment

The hydrometallurgical process entails the caustic or acid treatment of solid matrices to dissolve target elements from them. Precipitation, solvent extraction, distillation, ion exchange, cementation, or filtration are typical separation processes that come after this one. High selectivity to metals, low energy consumption, and the potential for reactant recycling are the key benefits of hydrometallurgical processes.

However, hydrometallurgical processes require mechanical pre-treatment to increase the active surface exposed to the reactants, a significant amount of solutions, and the production of effluent, which may be poisonous and/or caustic.

To recover PGM catalyst from PEMFCs, hydrometallurgical procedures typically involve pre-treatment, leaching, separation, and purification sub-processes. More sub-processes, including solvent regeneration, may be added in order to enhance the process's overall techno-economic performance. Leaching, separation, and precipitation alone have the highest individual recovery efficiencies.

Strong acid and oxidant solutions are leaching agents. Aqua regia, a 3:1 molar ratio solution of HCl and HNO3, is typically used for leaching in the recovery of PGMs from exhausted catalysts on a carbon support. However, leaching creates a very harsh environment because of the high acid content with a pH of 1. Following leaching, the PGM-containing solution goes through a filtration process to get rid of the carbon particles. Different methods can be used to separate PGM anions.

Duclos et al.[34] discovered two options for Pt:

(i) liquid-liquid extraction followed by platinum stripping; and

(ii) an anion exchange resin procedure followed by resin desorption.

The Pt-rich stream from the separation procedure is treated with NH_4Cl to precipitate platinum as $(NH_4)_2PtCl_6$. Pt is finally recovered in solid form after the stream has been filtered. High purity Pt (99.9%) can be obtained by adding a phase of ignition at 350 °C. According to experimental findings, Pt recovery efficiency can reach 76%. Alternately, $(NH_4)_2PtCl_6$ and carbon powder could be used to create fresh electrode ink.

Even though the procedure described in this section focuses on recovering Pt, other PGMs like iridium and ruthenium can also be recovered using it. It should be noted that this family of techniques could be utilized to recover Ni from SOFCs by altering the leaching agents.

2.4.2 Pyro-hydrometallurgical treatment

Pyro-hydrometallurgical treatment for PEM systems entails a calcination procedure in which GDLs, membranes, and electrodes are burned. PGMs are then recovered by precipitation from the combustion's by-product ashes after they have been treated through acid dissolution.

Pyro-hydrometallurgical methods, in contrast to hydrometallurgical treatment, do not call for mechanical pre-treatment and have greater recovery efficiencies but more energy requirements. The pyro-hydrometallurgical treatment's application is made possible by the treatment's quantity and ease of stages. However, the harsh working temperature and pH conditions cause safety and environmental problems.

A procedure based on this technology was published by Zhao et al.[35] They comprised the following key phases:

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[34] Environmental assessment of proton exchange membrane fuel cell platinum catalyst recycling, J. Clean. Prod., 142 (2017).

[35] Reclaim/recycle of Pt/C catalysts for PEMFC, Energy Convers Manag 2007.

(i) drying and calcination;

(ii) leaching and purification;

(iii) reduction and filtration.

MEA must first be dried at 80 °C for three hours. The dried MEA is next subjected to calcination at 600 °C for 6 hours to remove carbon and any remaining volatile chemicals. At 65 °C, HNO_3 is used to leach the calcine. The solution is heated to 110 °C and HCl is added as the next purification step. The obtained solid H_2PtCl_6 is subsequently dissolved at pH 3 - 4 using deionized water and NaOH. The addition of formic acid enables Pt reduction. Finally, Pt black is recovered via vacuum filtration and drying.

2.4.3 Hydrothermal treatment

Waste materials are processed using steam at a comparatively elevated temperature and pressure during hydrothermal treatment. Due to this procedure' complexity, it may take a while. The YSZ-containing compounds are disintegrated using water at 200 - 240 °C. Filtration is used to collect the powder, which is then heated to 50 °C and dried. The dry powder is next processed and screened until it is smaller than 100 mm. Cold isostatic pressing is performed after uniaxial pressing on the sieved micro-powder. To produce recycled zirconia, the resultant material is sintered at 1400–1600 °C for two hours.

2.4.4 Novel EoL Technologies

The technologies that are currently available are based on the adaptation of current techniques used for recycling devices with a similar level of complexity and a content of risky/precious/critical materials based on the hydrometallurgical process (HMT) for Pt salt recovery to re-manufacture the PEMFC. To recover ionomer using the alcohol dissolution (AD) process and reintegrate it in a cell, novel technologies are also being researched and developed; the electrochemical recovery route, which combines electrochemical leaching and electrodeposition, is optimized for precious metallic materials suitable for other markets and applications (please, see "Deliverable D1.2 - Technical report on adaptation of existing technology (hydrometallurgical process) for PEMFC material recovery: results and design").

The new EoL technologies for FCH products are covered in this section. While allowing for the extra recovery of other pertinent components like the membrane or the carbon support, these technologies are primarily focused on the recovery of Pt.

Selective electrochemical dissolution: Pt and carbon support recovery

The carbon support and catalyst from CCM MEAs may both be recovered using a unique electrochemical method that was proposed by Latsuzbaia et al.[36] The procedure is based on the electrochemical dissolution of materials at various voltage and pH windows. The CCM is electrochemically cleaned in the first stage. After that, oxygen is pumped into the system, and the voltage and pH windows are adjusted. The system operates at potentials below 1.2 V while the dissolution process is taking place, preventing corrosion of the carbon support and enabling its recovery. By altering pH and voltage settings, the technique might be used to the recovery of additional materials in various FCH devices.

Transient dissolution through potential alteration: Pt recovery

Hodnik et al.[37] suggested a technique for recovering Pt based on the metal's acid dissolution. The technique can be viewed as a different type of electrochemical dissolving process than what was described in the section above. It focuses on the transitory condition brought on by a cyclic alteration in the Pt surface's oxidation state. Chloride's presence during the transient period enables the stabilization of Pt ions. The oxidizing and reducing agents are O3 and CO, respectively. Up until the complete dissolution of Pt, the direction of the oxidation reaction on the Pt surface is cycled through.

The avoidance of external potential use, the high recovery yield, and the comfortable operating circumstances are this technology's main benefits. The additional recovery of other stack components like the membrane and the catalyst support is not taken into account, though. Finally, it should be mentioned that by modifying the working conditions, this process might be used to recover other metals including Ru, Ir, and Pd in PEMWEs and AWEs (e.g., the number and duration of the cycles).

Acid process: Membrane and Pt recovery

[36] Environmentally friendly carbon-preserving recovery of noble metals from supported fuel cell catalysts, ChemSusChem 2015.
[37] Platinum recycling going green via induced surface potential alteration enabling fast and efficient dissolution, Nat Commun 2016.

Xu et al.[38] suggested a brand-new acid technique for the recovery of PGMs. This route, in contrast to existing procedures, enables the effective recovery of both the PGM and the ionomer from CCM MEAs by the use of strong acids to oxidize the carbon support and subsequent separation procedures (filtration and centrifugation). The ability to regenerate the membrane for fresh stacks with adequate electrochemical performance is one of this technology' key characteristics.

This unique strategy has advantages over traditional methods, such as hydrometallurgical and pyro-hydrometallurgical ones, in terms of higher PGM recovery and a lack of harmful emissions. The main drawbacks of this technology, on the other hand, are the extreme pH conditions, the complicated chain, and the lengthy process.

Alcohol Solvent Process: Nafion membrane and Pt recovery

Shore[39] was granted a patent for a method that uses an alcohol solvent approach to recover noble metals and ionomers from PEM devices. The method described in this invention can be thought of as a pre-treatment that enables the subsequent recovery of the catalyst as well as the polymer resin. Under the influence of an alkyl alcohol solution, MEA layers delaminate in the first stage. Using a microwave heater, the temperature is raised until it reaches the ideal level for dissolution. For the subsequent separation by filter-pressing and ultra-filtration, the polymer's particle size in the dispersion is a crucial factor. The residence duration and temperature adjustments made by the microwave heater regulate this parameter. Overall, the procedure is characterized by mild pH, temperature, and voltage conditions. The economic viability of this recovery technology raises questions, though. Recycling the solvents in this way would lead to significant cost savings while also enhancing techno-environmental performance.

2.5 Applicable Standards to FCH End of Life

Governments do not write standards; instead, standardization groups do. Both public and private ones are possible. They frequently discuss product performance or quality control.

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[38] Recycling of membrane electrode assembly of PEMFC by acid processing, Int J Hydrogen Energy 2010.
[39] Process for recycling components of a PEM fuel cell membrane electrode assembly - US Patent 8124261B2, 2012.

Standards are optional, with the rare exception of when they are required by a national rule. It is advised to look into whether a product complies with any standards that may be in place for a particular product category. When it comes to product design and safety, standards boost confidence. By requiring performance tests, standards can also provide a better understanding of how well things work.

There is a distinct category of standards in Europe called harmonized standards. The European Commission commissions these to adhere to particular directives, such as the machine directive, the directive on gas appliances, and of course the Eco-design directive. The General Product Safety Directive 2001/95/EC 2 clearly encourages the use of harmonized standards because it is presumed that items made in accordance with such standards are safe.

The European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization are responsible for creating the harmonized standards (CENELEC). The International Electrotechnical Committee (IEC) and the International Standards Organization (ISO) frequently hand over standards to CEN and CENELEC, who then add provisions to bring the standards in line with European legislation on things like consumer protection, safety, and environmental protection. Online resources have a complete list of the harmonized standards. The application of these standards is still optional, but producers are then required to demonstrate that their products adhere to the fundamental requirements outlined in each relevant regulation.

Standards are created with varied objectives, can combine multiple objectives, and can encompass many life cycle phases, including:

- Design;
- Production;
- Transport;
- Installation;
- Performance tests;
- Safety design;
- Safety tests;
- Environmental protection;
- Use;
- Return.

The international organizations for standardization that oversee the standardization of fuel cell technology are:

- International Electrotechnical Commission, **IEC TC 105**;
- International Standardisation Organisation, ISO/TC 197 (Hydrogen Technologies).

Through the work of the Technical Body **CLC/SR 105**, the European Committee for Electrotechnical Standardization, or CENELEC, is involved with fuel cell technology on a European level.

2.5.1 IEC TC 105 Scope and Standards[40]

IEC TC 105's mission is to develop international standards for fuel cell (FC) technologies for all FC types and associated applications, including stationary FC power systems for distributed power generators and combined heat and power systems, stationary FC power systems for transportation applications, including propulsion systems (see note below), range extenders, auxiliary power units, portable FC power systems, micro FC power systems, reverse operating FC power systems, and general electrochemical applications.

Below is a list of the standards that the TC has produced. It is noticeable that recycling and EoL norms are completely absent.

Table 4: IEC TC 105 standards.

Reference	Title	Related Committee
105/894/CDV	IEC 62282-4-102 ED2: Fuel cell technologies - Part 4-102: Fuel cell power systems for propulsion other than road vehicles and auxiliary power units (APU) - Fuel cell power systems for electrically powered industrial trucks - Performance test methods	
105/902/CDV	IEC 62282-6-401 ED1: Fuel cell technologies - Part 6-401: Micro fuel cell power systems - Power and data interchangeability - Performance test methods for laptop computers	TA 19
105/908/CD	IEC 62282-8-201 ED2: Fuel cell technologies - Part 8-201: Energy storage systems using fuel cell modules in reverse mode - Test procedures for the performance of power-to-power systems	TC 120
105/912(F)/FDIS	IEC 62282-4-101 ED2: Fuel cell technologies - Part 4-101: Fuel cell power systems for electrically powered industrial trucks - Safety	
105/912/FDIS	IEC 62282-4-101 ED2: Fuel cell technologies - Part 4-101: Fuel cell power systems for electrically powered industrial trucks - Safety	

40 IEC TC 105 Fuel Cell Technologies.

105/914(F)/FDIS	IEC 62282-4-600 ED1: Fuel cell technologies - Part 4-600: Fuel cell power systems for propulsion other than road vehicles and auxiliary power units (APU) - Fuel cell/battery hybrid systems performance test methods for excavators	TC 21
105/914/FDIS	IEC 62282-4-600 ED1: Fuel cell technologies - Part 4-600: Fuel cell power systems for propulsion other than road vehicles and auxiliary power units (APU) - Fuel cell/battery hybrid systems performance test methods for excavators	TC 21
105/916/CDV	IEC 62282-8-301 ED1: Fuel cell technologies - Part 8-301: Energy storage systems using fuel cell modules in reverse mode - Power to methane energy systems based on solid oxide cells including reversible operation - Performance test methods	
105/935/CD	IEC 62282-2-400 ED1: Fuel cell technologies - Part 2-400: Fuel cell modules - Calculation of Rated Power and Power Density of a PEM stack and PEM module	
105/941/CDV	IEC 62282-4-202 ED1: Fuel cell technologies - Part 4-202: Fuel cell power system for unmanned aircrafts - Performance test methods	
105/947(F)/FDIS	IEC 62282-4-102 ED2: Fuel cell technologies - Part 4-102: Fuel cell power systems for electrically powered industrial trucks - Performance test methods	
105/947/FDIS	IEC 62282-4-102 ED2: Fuel cell technologies - Part 4-102: Fuel cell power systems for electrically powered industrial trucks - Performance test methods	
105/949/CDV	IEC 62282-6-101 ED1: Fuel cell technologies - Part 6-101: Micro fuel cell power systems - Safety - General requirements	
105/950/CDV	IEC 62282-6-106 ED1: Fuel cell technologies - Part 6-106: Micro fuel cell power systems - Safety - Indirect Class 8 (corrosive) compounds	
105/951/CDV	IEC 62282-6-107 ED1: Fuel cell technologies - Part 6-107: Micro fuel cell power systems - Safety - Indirect water-reactive (Division 4.3) compounds	
105/961/CD	IEC 62282-3-202 ED1: Fuel cell technologies - Part 3-202: Stationary fuel cell power systems - Performance test methods for small fuel cell power systems that can be complemented with a supplementary heat generator for multiple units operation by an energy management system	TC 8 TC 57 TC 120 SyC Smart Energy

105/963/CD	IEC 63341-3 ED1: Railway applications - Rolling stock - Part 3: Fuel cell systems for propulsion - Performance test methods	TC 9
105/894/CDV	IEC 62282-4-102 ED2: Fuel cell technologies - Part 4-102: Fuel cell power systems for propulsion other than road vehicles and auxiliary power units (APU) - Fuel cell power systems for electrically powered industrial trucks - Performance test methods	

2.5.2 EN 4555X Series

The European Commission's standardization request M/543 led to the development of the dual logo CEN-CENELEC standardization deliverables, which are in the 45550–45559 range numerically and could apply to any product covered by the Energy-Related Products (ErPs) - better known as Ecodesign Directive (2009/125/EC) - see section 2.2.2 .

The subjects included in the aforementioned standardization request are related to the following dimensions of material efficiency::

a. Extending product lifetime;
b. Ability to re-use components or recycle materials from products at end-of-life;
c. Use of re-used components and/or recycled materials in products These standards are general in nature and describe or define fundamental principles, concepts, terminology or technical characteristics.

They may be used in conjunction with other standards that are group- or product-specific, such as those created by product technical committees.

CLC/TR 45550

This document offers an alphabetical list of all terms that have been approved for use in CEN–CLC standards in the number range 45554–45555. Such terms are intended to be used in other material efficiency standards that have been produced based on CENCLC standards and fall within the numeric range of 45552-45559, or standards that are meant to supplement that series. Additionally, they serve as the foundation for the creation of new definitions for material efficiency standards that are relevant to specific products.

CLC/TR 45551

In accordance with M/543, this Technical Report offers instructions on how to write product-specific standardization deliverables using general material efficiency criteria. When creating product-specific standards on topics already addressed by general standards on material efficiency, it is intended to be used by the CEN and CENELEC product TCs.

EN 45552

General method for the assessment of the durability of Energy-related Products (ErP)

This document describes a broad procedure for evaluating the dependability and longevity of ErPs. Reliability is an evaluation of the likelihood of time between the first usage and the first failure, or in between failures. Durability, as opposed to likelihood, is the entire anticipated time for this same period. In order to evaluate the dependability and durability of ErPs, it offers a generic assessment approach that is meant to be customized for application at the product or product-group level.

With a predetermined method of maintenance and repair being employed, durability is a feature of the product to maintain the serviceability until a marginal state is approached (ISO 11994).

The ability of an item to perform a required function under given conditions of use and maintenance, until a limiting state is reached, is included in the concept of durability (IEV 192-01-21), as is the ability to perform as required, under given conditions of use and maintenance, until the end of useful life (ISO 14708-5).

Using this standard as a foundation, product/product group standards must fill the following gaps:

- Define product/product group priority functions/parts;
- Define environmental/operating conditions;
- Describe test procedures to evaluate priority part reliability;
- Define "Limiting states" leading to Potential "End-of-Life" states.

EN 45553

General method for assessing the ability of an ErP to be remanufactured

This standard presents a general approach to evaluating a product's potential for remanufacturing in the energy sector. Technical committees are supposed to apply it while creating horizontal, generic, and product- or product-group-specific standards. Throughout this text, references to "user of this document" apply to both people who are directly using the standard as well as members of technical committees that are producing horizontal, general, and product, or product-group, standards. This article does not examine how easily a component that is not regarded as an energy-related product can be remanufactured. In this document, only the requirements for an energy-related product's re-manufacturability are discussed.

Product-specific standards are needed to fill in the following gaps:

- Determine the characteristics that are unique to the product or product group;
- Relevant parameter evaluation and scoring must be product specific.

EN 45554

General methods for the assessment of the ability to repair, reuse and upgrade energy-related products

This document provides generic methods to assess the following aspects:

1. the ability of products to be repaired;
2. the ability of products, or parts thereof, to be reused;
3. the ability of products to be upgraded.

It offers general standards and techniques for evaluating whether specific product components can be taken out and repaired, reused, or upgraded. Priority Parts needs to be identified using the assessment procedure outlined in EN 45552. When a product is introduced to the market, the procedures described in this document contain product, and support, related criteria, taking into consideration information on parts that are likely to malfunction, need to be replaced, or have the potential to be reused. A product's suitability for repair, reuse, or improvement depends on a number of variables, including health and safety, as well as economic, legal, and environmental considerations. It is outside the purview of this paper to discuss whether it is reasonable to repair, reuse, or upgrade products.

EN 45555

General methods for assessing the recyclability and recoverability of energy-related products

This document establishes general principles for:

- Assessing the recyclability of energy-related products;
- Assessing the recoverability of energy-related products.

It also considers:

- The ability to access or remove certain components, assemblies, materials or substances from products to facilitate their extraction at the end-of-life for ease of treatment, recycling and other recovery operations;
- The recyclability of critical raw materials (CRMs).

This standard specifies the characteristics that can be used to create standards for individual products or groups of products and determine their rates of recoverability and recycling. Instead of being used directly, this document serves as a guide for creating product or product-group standards. For product or product group standards, additional details and requirements not covered in this text will be required. In the absence of product standards based on this document, this document is not relevant to generate publicly available product information or compare products. The word "product" is used throughout the rest of the document even though it can be used for a product or product-group for the benefit of easier reading. Product group standards need to be created.

EN 45556

General method for assessing the proportion of reused components in energy-related products

This document examines how to estimate the proportion of recycled materials in energy-related products on a general level that can be used at any stage of the product's lifespan. This guide is meant to be used by product technical committees when creating standards for individual products or groups of products. Where there is no product-specific standard, this document may be used. The scope of this document does not include factors like performance, validation, verification, and acceptability of reused components.

EN 45557

General method for assessing the proportion of recycled material content in energy-related products

It outlines a generic procedure for determining how much recycled material is present in an energy-related product. This document can be used to define the framework for evaluating the amount of recycled materials in particular product categories.

The definitions of "pre-consumer materials" and "post-consumer materials" are of particular importance, where:

- **Pre-consumer material**: a material that is used instead of being wasted during a manufacturing process, excluding materials that are recycled back into the original process that produced them, such as rework, regrind, or scrap;

- **Post-consumer material**: material recovered from waste produced by individuals or by institutional, industrial, and commercial facilities acting as the final consumers of a finished good.

A schematic representation of the material flow of “pre-consumer material” and “post-consumer material” il given in figure :

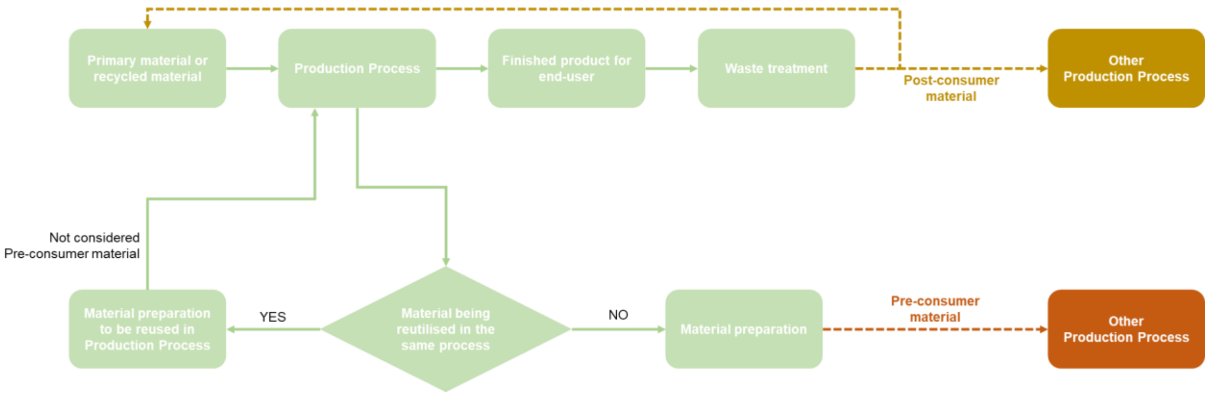

Figure 16: Pre-consumer and post-consumer material flow.

In the absence of a product specific standard based on this document, it is not intended to generate publicly available product information and compare products. Aspects like the quality and physical characteristics of recycled materials are not covered in this document. The evaluation of repurposed components is not covered by this specification.

EN 45558

General method to declare the use of critical raw materials (CRM) in energy-related products

This document's primary purpose is to offer a way for data on the use of CRMs to be shared with other pertinent stakeholders and up and down the supply chain. Any public, commercial, or social companies engaged in the production of ErP, such as producers of energy-related goods (including SMEs), as well as other organizations in the product supply chain, could be potential consumers of this document. It is also pertinent to European policy makers and market monitoring and trade regulators. The horizontal nature of this document allows it to be immediately applied to any energy-related product. This document suggests using the EN IEC 62474 materials declaration standard to provide a standardized method for declaring the usage of CRMs in energy-related products. However, no specific technique or technology for gathering CRM data is described in this article. This paper does not cover process chemicals, manufacturing emissions, or packaging emissions.

EN 45559

Methods for providing information relating to material efficiency aspects of energy-related products

The information sharing procedure for the material efficiency (ME) features of ErPs is established in this document. It has two main goals:

- it stipulates that publications on general or horizontal ME topics must contain a clause outlining the specific topic-related information that must be reported; and
- it provides a general method for developing a communication strategy that will be applied when preparing product-specific, or product-group, publications.

EN 50693 (Addition to EN 4555X Series)

The Product Category Rules (PCR) for electronic and electrical items and systems are defined in the document (EEPS). It outlines the steps and specifications for conducting life cycle assessments within the framework of environmental declarations. Additional product-specific rules (PSR) are added to PCR to further define concepts like functional units and default circumstances in the context of the particular product. As a result, it also offers instructions on how to develop PSR in pertinent technical committees.

This paper offers standard guidelines for three different life cycle assessment (LCA) processes:

- the LCA report;
- the development of product-specific rules; and c) the life cycle assessment (LCA) itself.

Additional rules for environmental declarations are provided in this publication. The fundamental LCA framework and principles are not covered by the standard because they are based on the EN ISO 14040 set of standards (i.e., EN ISO 14040 and ISO 14044).

2.5.3 Standards related to the Recycling of Batteries

Similar criteria for batteries have been looked at in order to evaluate the current state of FCH recycling and EoL standards. Similar circumstances, including a lack of exact and explicit directives and/or standards, appear to apply to batteries.

- The present regulations do not provide enough explicit information or instructions on battery recycling;
- The most significant labelling standard, IEC 62902, provides the least information on the material composition of batteries. The claim is that it should not be too obvious which Li-ion battery has the highest recycling potential. A traceability system or database, however, can close this information gap;
- New active materials, such as a silicon-based anode, must be anticipated in standards that specify battery marking and include the main active materials (i.e., IEC 62620, IEC 61960);
- It is encouraged to use standardized calculation techniques for recycling efficiency to prevent data misunderstanding. Environmental considerations like waste streams, energy-recovery incineration, and eventual landfilling or deletion should be included;
- It is necessary to quantify essential indicators in a consistent manner, such as CO2 footprint, recycling %, toxicity, and recycling cost.

2.6 Standards on Circularity Principles

A circular economy is a framework designed to reduce waste, conserve resources, and boost material value. For European businesses and consumers, the shift to a circular economy presents a once-in-a-lifetime chance to create innovative, sustainable competitive advantages. An innovative method for ensuring sustainable economic growth is provided by the circular economy. The circular economy asks for rethinking how resources are managed and how waste is viewed in order to replace a linear paradigm where items are made, utilized, and disposed of. It is founded on cyclical mechanisms that allow materials and products to be reused, mended, upgraded, remanufactured, and finally recycled.

As part of its Green Deal and Circular Economy Action Plan, the European Union has made achieving a circular economy a top priority. The EU and the Indian Government adopted a Joint Declaration on Resource Efficiency and Circular Economy in July 2020 to further solidify their commitment to the circular economy. The EU and India hope to support and improve their communication and collaboration in this field through this declaration.

The delivery of this can be facilitated by standardization. In order to assist European industry in making the transition to a fully operational circular economy, CEN and CENELEC are working on this. With the slogan "Standards Build Trust," CEN and CENELEC have also recently highlighted how standards aid in the advancement of European and global initiatives, such as the UN Sustainable Development Goals. Standards support the implementation of resource and energy sustainability while safeguarding customers, employees, and the environment. Closing resource loops and maintaining the worth and calibre of resources throughout the cycle are the greatest ways to accomplish this goal. Two specific instances of CEN and CENELEC Technical Committees devoted to easing the transition to a Circular Economy are given in this pamphlet.

In this regard, the technical committee IEC TC 111 creates universally applicable horizontal standards for environmental concerns. IEC TC 111 is currently working on a number of circular economy-related standards, such as a general method for determining the percentage of recycled materials in goods, recommendations for material circularity considerations in environmentally aware design, and sustainable waste management.

Furthermore, the Standardization Management Board (SMB) receives advice on environmental matters, such as the circular economy and material efficiency, from the Advisory Committee on Environmental Aspects (ACEA). The IEC community has been informed by ACEA about the circular economy and the function of standards.

2.6.1 CEN/CLC/JTC 10 - Material efficiency aspects for products in scope of Ecodesign legislation

The objective of this technical committee is to produce documentation on material efficiency issues for goods covered by the Ecodesign Directive 2009/125/EC and any further updates by creating generic and horizontal CEN-CENELEC publications on a range of issues related to material efficiency, including (but not limited to):

- Increasing a product's lifespan;
- Capacity to repurpose parts or recycle materials from items at the end of their useful lives;
- Use of repurposed parts or recycled materials in products, including consideration of the Essential Raw Materials list established by the European Commission (CRM).

prEN 45560 - Method to achieve circular designs of products

Still undergoing the drafting process, with the help of this standard, manufacturers of goods covered by the Ecodesign Directive can create designs that are circularly compatible. The suggested method's guiding concepts, specifications, and instructions are described in depth. With the help of this paper, a company can integrate circularity into the planning and creation of its goods. The circular categories set by an organization must be met by the product design guidelines that will be developed with the assistance of this document (e.g., the circular business models chosen by the organization, the legislation requirements).

Any size and kind of company can use it. In the framework of the circular economy's technical cycles, it focuses on material efficiency. This standard offers advice on how to lessen environmental effects and how to manage difficulties like trade-offs during product design. It bases its principles on the life cycle thinking.

2.6.2 IEC TC 111 Scope and Standards[41]

In order to promote common technical approaches and solutions, the technical committee's mandate is to develop the necessary guidelines, basic and horizontal standards, including technical reports, in the environmental area, working closely with the IEC product committees, which maintain their independence in handling the environmental issues that are pertinent to their products.

All of this is done while maintaining constant communication with ACEA and ISO/TC 207 and keeping a close eye on the relevant global regional standardization initiatives in order to become a focal point for standardization-related issues.

The scope does not include EMC/EMF aspects.

[41] IEC TC 111 Environmental standardization for electrical and electronic products and systems.

Table 5: IEC TC 111 standards.

Reference	Title	Related Committee
111/654/DTS	IEC TS 62474-1 ED1: Material declaration for products of and for the electrotechnical industry: Guidance for the implementation of IEC 62474.	
111/655/CDV	IEC 63333 ED1: General method for assessing the proportion of reused components in products	ACEA TC 2, 9, 18, 21, 23, 34, 34D, 59, 62, 65B, 80, 82, 88, 100, 110, 121, 124, 125
111/657/CDV	IEC 62321-3-4 ED1: Part 3-4: Screening of Phthalates in polymers of electrotechnical products by high performance liquid chromatography with ultraviolet detector (HPLC-UV), thin layer chromatography (TLC) and thermal desorption mass spectrometry (TD-MS)	
111/668/CD	IEC 63372 ED1: Quantification and communication of Carbon FootPRINT and GHG emission reductions/avoided emissions from electric and electronic products and systems. Principles, methodologies, requirements, and guidance	TC 17, **105**, 120, 121 SC 21A SC 22H
111/670/CD	IEC 82474-1 ED1: Material declaration. Part 1: General requirements	TC 121
111/685/CD	IEC 62321-13 ED1: Determination of certain substances in electrotechnical products. Part 13: Bisphenol A in plastics by liquid chromatography-diode array detection (LC-DAD), liquid chromatography-mass spectrometry (LC-MS) and liquid chromatography-tandem mass spectrometry (LC-MS/MS)	
111/689(F)/FDIS	IEC 62321-12 ED1: Determination of certain substances in electrotechnical products - Part 12: Simultaneous determination. Polybrominated biphenyls, polybrominated diphenyl ethers and phthalates in polymers by gas chromatography-mass spectrometry	
111/689/FDIS	IEC 62321-12 ED1: Determination of certain substances in electrotechnical products - Part 12: Simultaneous determination. Polybrominated biphenyls, polybrominated diphenyl ethers and	

	phthalates in polymers by gas chromatography-mass spectrometry
111/692/CD	IEC 62321-8 ED2: Determination of certain substances in electrotechnical products - Part 8: Phthalates in polymers by gas chromatography-mass spectrometry (GC-MS), gas chromatography-mass spectrometry using a pyrolizer/thermal desorption accessory (Py-TD-GC-MS)

2.7 Ecodesign Standards

About 25 CEN and CENELEC Technical Committees work to create European Standards in the areas of Ecodesign and energy labelling, and as regulations change at the level of the European Commission, their membership is likely to grow over time. Current CEN and CENELEC Technical Committees working in this area address a wide range of subjects, including but not limited to: Household electrical appliances, professional refrigeration, heating boilers, power transformers, kitchen appliances and so on.

The CEN-CENELEC Ecodesign Coordination Group was established in November 2012 by the CEN and CENELEC Technical Boards to coordinate and provide advice on standardization work in the fields of Ecodesign and energy labelling (Eco-CG). The group acts as a focal point for issues connected to standardization for the Ecodesign Standardization Requests submitted under Directive 2009/125/EC on Ecodesign of Energy-Related Products and Regulation (EU) 2017/1369 on Energy Labelling of Energy-Related Products and their future revisions.

According to the Ecodesign and Energy Labelling Framework Directives, there are currently no references to harmonized standards that have been published in the Official Journal of the European Union. There are no recognized standards for FCHs' eco-design that are currently in use.

In this context, the eGHOST project seeks to set a first benchmark for the eco-design criteria/standards in the European hydrogen industry. One of its objectives is to support the definition of technical screening criteria in other environmental aspects for the EU taxonomy. Another goal is to create prospective metrics for social and environmental aspects that will be incorporated into the EU taxonomy. A third goal is to support the European hydrogen industry's CSR. A fourth goal is to lay the groundwork for future eco-design regulations in accordance with the Eco-design Directive.

Another important objective of the project is to develop both general eco-design guidelines for FCH goods as well as eco-design recommendations particular to each of the two main FCH products.

3 Survey

3.1 Methodology of the Work

Due to the scarcity of guidelines on standardisation and to the difficulties linked to the individuation of applicable standards from standardisation bodies, a standardization survey has been launched and shared with FCH technologies (PEMFC and SOFC) providers internal and external to the project. The purpose of this survey is to evaluate from manufacturer point of view what is the approach to the recovering of critical raw material of EoL Fuel Cells, in particular Pt and ionomer for PEMFC, and Ni, YSZ, La and Co for SOFC. In the survey the awareness of manufacturers regarding the standards applicable to Hydrogen Fuel Cells manufacturing, handling, and dismantling/recycling has been investigated, as well as Eco-design topic, asking what the approach and other aspects is linked to Eco-design, such as weight and volume reduction of FCHs, and products design change in order to optimize the recycling and disassembling phase. In order to guide the partners to fill the survey, some Teams calls have been conducted.

Here following the link to the Best4Hy Standardisation Survey:

https://ec.europa.eu/eusurvey/runner/BEST4HYstdSurvey

Here below are reported the technical questions contained in the survey.

- What kind of FCH is handled by your organization/sector?
- Have you liaised, for aspects related to Hydrogen Fuel Cells manufacturing, handling, and dismantling/recycling, with any Standards Developing Organization (SDO), National Standardisation Body (NSB) or Technical Committee (TC)?
- If “yes” was the interaction mandatory for compliance with any regulation/law/standard or voluntary?
- Please specify which one(s) and the reason(s) of your interaction with SDO, NSB or TC.
- How important do you consider standardisation in your organization with regards to Hydrogen Fuel Cells manufacturing, handling, and dismantling/recycling, being 1 “of no importance” and 5 “of major importance”?
- Did you encounter any risk related to standardisation of Hydrogen Fuel Cells related activities in your organization?
- What percentage of your turnover is dedicated to expenses related to standardisation of Hydrogen Fuel Cells related activities?
- Have you carried out a review of the standards applicable to Hydrogen Fuel Cells manufacturing, handling, and dismantling/recycling?
- If “yes” please list as many as possible standards that are applicable to your organization.
- In addition to the standards covered in the previous questions, please list other EU/National/Regional directives or laws that are applicable to your organization/sector with regards to Hydrogen Fuel Cells manufacturing, handling, and dismantling/recycling.
- Are you involved in Working Groups on Standardization in Hydrogen Fuel Cells manufacturing, handling, and dismantling/recycling?

- If “yes” please list the member of the working group(s).
- How is your approach in eco-design? Would you be interested in rethinking the design of your products?
- One aspect to take in consideration in Eco-Design is the weight and volume reduction of FCHs. How much could you reduce it?
- How could you reach the reductions?
- Another aspect is the use of recycled materials. What is your actual position?
- Do you have a quality internal control of the material or guarantees to use recycled materials?
- Another aspect linked to Eco-Design is the incorporation of used materials in FCHs. Does this imply a new design of your products in order to optimize the recycling and disassembling phase? What is your position?
- Up to now, what is your position regarding EoL devices? Do you have collected some of them from your end users?
- If your previous answer is yes, how many EoL devices do you have received from your end users?
- Please report the main details of the EoL devices, also in terms of weight.
- Do you have a dedicated internal area/unit that works on EoL?
- If yes, detail your approach (if not also detail what is your approach on the matter).
- Do you think could be profitable for you to have an internal EoL dedicated sector?

3.2 Online Survey Results

Currently, six partners have completed the survey, all from industry companies. Three of them are handling PEMFC, one PEMFC and SOFC, one SOFC, and one SOFC and SO-electrolysers.

Four of the companies that answered had interactions with any Standards Developing Organization (SDO), National Standardisation Body (NSB) or Technical Committee (TC); for two of them the interaction was mandatory for compliance with regulations/law/standards. The organizations that were reported to have interacted with are:

- ISO;
- IEC;
- DKE/K 384 national mirror committee to IEC/TC 105, DKE/K 384, responsible for the development of standards for fuel cell technologies for all fields of application (DIN EN IEC 62282-2, IEC/TC 05/WG 12, EN50465, CEN/CLC JTC 17);
- VDMA - Verband der Deutschen Automobilindustrie;
- NOW GmbH - Nationale Organisation Wasserstoff- und Brennstoffzellentechnologie;
- Hydrogen Council.

In general, all the interviewed partners have expressed high importance for standardisation topic in their organization with regards to Hydrogen Fuel Cells manufacturing, handling, and dismantling/recycling. The main risks reported that could be linked to Hydrogen Fuel Cells related activities are:

- Financial efficiency in manufacturing and recycling

- Test procedures, e.g. for leakage testing, can thus be covered by different methods and not only by one single method, which may not be available in the own company.
- Difficulties in standardization of the fuel cell industry since it is composed of different technologies using also different materials.

The percentage of their turnover dedicated to expenses related to standardisation of Hydrogen Fuel Cells related activities has been reported to be extremely low and <5%.

All the partners interviewed have carried out a review of the standards applicable to Hydrogen Fuel Cells manufacturing, handling and dismantling/recycling.

The standards that have been indicated are:

Standard	Title
ISO9001:2015	Quality management systems — Requirements
EN 60079-10-1:2021	Explosive gas atmospheres
EN 60079-14:2014	Guidance for equipment for use in explosive atmospheres in environment
EN 61000-6-2:2019	Electrical and electronic equipment intended for use in industrial locations
EN 61000-6-4:2019	Electrical and electronic equipment intended for use in industrial locations
EN 62282-3-200:2016	Operational and environmental aspects of the stationary fuel cell power systems performance
EN ISO12100:2011	Safety of machinery — General principles for design — Risk assessment and risk reduction
EN1090	Factory Production Control system for the production of steel and aluminium components
IEC 60068 series	Environmental testing
IEC 60204 series	Electrical equipment of machines
IEC 60309 series	Plugs, socket-outlets and couplers for industrial purposes
IEC 60335 series	Functional safety standard for electrical appliances for household and similar purposes
IEC 60664 series	Insulation coordination for equipment within low- voltage systems
IEC 60721 series	Environmental parameters and their severities to which products together with their packaging
IEC 62023	Structuring of technical information and documentation
IEC 62061 series	Requirements and recommendations for the design, integration and validation of safety-related control systems
IEC 62282 series	Fuel cell modules - Safety
IEC 62282-3-100	Fuel cell technologies - Part 3-100: Stationary fuel cell power systems - Safety
IEC 62477 series	Safety requirements for power electronic converter systems and equipment
ISO 23273:2013	Fuel cell road vehicles — Safety specifications — Protection against hydrogen hazards for vehicles fuelled with compressed hydrogen

ISO14687-2	Hydrogen fuel — Product specification — Part 2: Proton exchange membrane (PEM) fuel cell applications for road vehicles
ISO14687-3	Hydrogen fuel — Product specification — Part 3: Proton exchange membrane (PEM) fuel cell applications for stationary appliances
ISO15916	Basic considerations for the safety of hydrogen systems
ISO9001:2015	Quality management systems — Requirements
EN 60079-10-1:2021	Explosive gas atmospheres

Almost all of the partners that have answered are involved in working groups on standardization such as IEA-HIA task.

In addition to the standards collected thanks to the survey, a non-exhaustive list of the standards utilized in the manufacturing process are listed in table 5 based on data gathered with the assistance of one of the BEST4Hy project's partners who manufactures FCHs.

To better fit the scope of this deliverable and illustrate the current state of the manufacturing supply chain applicable standards, the original list of standards has been refined (more to follow in the results of the survey).

The standards have been categorized, and while there are readily available standards on terminology and general subjects, like safety and component testing, there is little information or advice provided on disposal procedures.

US Public Law 89-272, the only disposal norm on the list, is not relevant to this work since it makes no explicit reference to FCH or any other related technologies.

Table 6: Manufacturing Process applicable standards.

Category	EU	International	USA	Title
Components	-	ICS 27.070	-	Proton exchange membrane fuel cell - Part 3: Test method for proton exchange membrane
Components	-	IEC / TS 62282-7-1:2010	-	Single cell test methods for polymer electrolyte fuel cell (PEFC)
Components	-	ICS 27.070	-	Proton exchange membrane fuel cell - Part 4: Test method for electrocatalysts
Components	-	ICS 27.070	-	Proton exchange membrane fuel cell - Part 6: Test method of bipolar plate properties
Components	-	ICS 27.070	-	Proton exchange membrane fuel cell - Part 5: Test method for membrane electrode assembly
Components	-	ICS 27.070	-	Proton exchange membrane fuel cells—Part 7: Test method of carbon paper properties
Components	-	ISO 4593:1993	-	Plastics membrane and sheeting - Determination of thickness by mechanical scanning

Disposal	-	-	Public Law 89–272, As Amended Through P.L. 115–232	Solid Waste Disposal Act
Electric and Electronic Products	not found	IEC 60050 (482):2003	-	Electrotechnical terminology - Primary and secondary cells and batteries
Electric and Electronic Products	DIN EN 60068-5-2	IEC 60068-5-2	-	Environmental Testing for Electric and Electronic Products: Terms and definitions
Electric and Electronic Products	DIN EN 50178 (VDE 0160)	-	-	Electronic equipment for use in power installations
Electric and Electronic Products	DIN EN 61000-4-2	IEC 61000-4-2	-	Electromagnetic compatibility (EMC)
Electric and Electronic Products	DIN EN 61000-4-3	IEC 61000-4-3	-	Electromagnetic compatibility (EMC)
Electric and Electronic Products	DIN EN 61000-4-8	IEC 61000-4-8	-	Electromagnetic compatibility (EMC)
Electric and Electronic Products	DIN EN 61000-4-5	IEC 61000-4-5	-	Electromagnetic compatibility (EMC)
Electric and Electronic Products	DIN EN 61000-4-4	IEC 61000-4-4	-	Electromagnetic compatibility (EMC)
Electric and Electronic Products	DIN EN 61000-4-6	IEC 61000-4-6	-	Electromagnetic compatibility (EMC)
Fuel Cell Power System	-	-	-	Proton exchange membrane fuel cell power supply system for power distribution substation
Fuel Cell Stack	-	ICS 27.070	-	Proton exchange membrane fuel cell - General technical specification of fuel cell
Fuel Cell Stack	DIN EN 62282-2 (VDE0130-201):2008-1	IEC 62282-2-100	-	Fuel Cell Modules
Fuel Cell Stack	EN 62282-2:2012 VDE 0130-2:2013-01	IEC 62282-2:2004	-	Fuel cell technologies - Part 2: Fuel cell modules
General	DIN EN 60950-1	IEC 60950-1:2005	-	Information technology equipment - Safety - Part 1: General requirements (IEC 2005)

	(VDE 0805-1)			
General	DIN IEC/TS 62282-1 (VDE V 0130-1):2011-03	IEC/TS 62282-1:2010	-	Fuel cell - Terminology
General	-	ISO 11469:2017 (part)	-	Material Identification and Labels of Automotive Plastic parts, Rubber Parts and Thermoplastic Elastomer Parts

Another topic of interest for interviewed manufacturers has been demonstrated to be the eco-design; all of them foresee a weight and volume reduction for their FCHs (from 10 to 30% of the total). The main idea to reach this goal is to optimize the equipment and to increase the power density, which would result in a reduction of weight per power output (kW/kg). This can be reached by optimizing components. Measures are better performing materials like CCMs, GDLs, BPPs and flow fields and the combination to find the best balance of power density and lifetime. Cost is another factor, which is crucial for private sector companies. The reduction of material mass from lessons learned from other products produced in our company can also achieve these goals. Bionic optimization of e.g. housing or of endplates of the fuel cell, alternative sealing systems which need less sealing material, optimized and weight reduced clamping systems, thinner bipolar plates reduce the weight of the product.

Another aspect related to eco-design is the use of recycled materials in FCHs. The general idea is to fully support the introduction of recycled materials in FCHs, although most of the partners see it as a future topic, as for now it is at R&D stage. Indeed, the "mass market" for fuel cells is not expected until the near future. Until now produced material is still widely available, while returned products who could provide recycled material are not widely available yet.

The incorporation of used materials in FCHs, another aspect linked to eco-design, is another aspect that is being assessed for the future, but right now there are not many ideas, also because the use of recycled materials would result in a redesign of the equipment. Only one manufacturer has reported the use of recycled membranes in their PEMFC.

For R&D purposes all the interviewed manufacturers collect EoL devices (mainly Fuel Cells) from the customers and end-users; the average number is 50 or more total devices received, corresponding to some ten of kg of materials received.

Not all the manufacturers have already a dedicated sector in the company that works on EoL devices, but they are planning to invest on it since they see it profitable in the future.

4 Identified standards gaps and standardisation: Road mapping proposals

The current standardisation about End of Life of Fuel Cell technologies is lacking specific documents and directions.

While generic standards on safety, testing and hydrogen quality are in place, there is still need to put effort in the definition of standards related to:

- The recycling of CRM and Hazardous Materials specifically used in the manufacturing of FCH;
- Explicit information and guidance on FCH recycling. The roles of the Manufacturers and Recycling parties are not specified, leading to *ad personam* solutions often by means of bilateral agreements;
- Unified guidelines or harmonized approaches for performing LCA do not exist, and different analyses may yield conflicting results when second use applications are considered, due to variability in assumptions, scope of the application and scenarios (e.g. considerations for recycling, costs and energy involved in manufacturing);
- End of Life and Eco-design standards are more than welcome. Standards that define FCH making and testing need to include and anticipate recyclability potential of CRM/REE/Hazardous materials and include harmonised calculation methods for recyclability of such materials. The inclusion of Environmental aspects is also required.

Starting from these lacking areas it is possible to have the possible direction for the next steps in the development of new standards.

First of all, it is important to develop and ensure a standardized terminology for FCHs, alongside with general guidance for FCH recycling.

Secondly, the standardization framework regarding the information on parts of the FCH product that are likely to malfunction should be developed. The same goes for parts that, need to be replaced, or have the potential to be reused, which depends on a number of variables, including health and safety, as well as economical, legal, and environmental considerations, that could also lead to the development of unified guidelines for LCA procedures.

After this, the focus could be directed towards an Ecodesign approach, for example a standardized method for assessing the proportion of reused components and recycled materials in FCH products. For this approach, results from other cross-cutting projects are also to be taken into account.

Lastly it will be useful to develop real standards on End-of-Life treatments and guidelines. In order to do this, it will be smart to start the most promising technologies for the EoL treatments of FCHs technologies.

Other deeper evaluations and guidelines for policies will be subject of the D6.3 Regulatory and Standards stakeholders activities outcomes and guidelines for policies.

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5 Conclusions

The deliverable has considered existing regulations and standards related directly to hydrogen technologies and/or to similar classes of products and systems with the aim of identifying how eco-design and treatment at end of life are currently regulated. With a similar objective, extra-European members of the Advisory Board have been contacted to understand if other regulatory systems have already tackled the issue. Finally, a survey has been undertaken amongst producers of hydrogen technologies.

The Sustainable Products approach introduced by the European Union with the review of the Ecodesign Directive might be applicable also to hydrogen technologies. It is however still just a proposal and there will be a need for further legislation to implement the approach. Significantly, the Ecodesign Directive has informed the drafting of the harmonised standards series 4555x, which deal with material efficiency in terms of extending product lifetime; ability to re-use components or recycle materials from products at end-of-life and employ of re-used components and/or recycled materials in products. These standards are general in nature and describe or define fundamental principles, concepts, terminology or technical characteristics, which are useful to set a level playing field for the operators implementing the Ecodesign Directive.

The Batteries Regulations aim to manage the surge in production required to meet the upcoming needs for batteries for mobility and storage of energy. Many critical raw materials are used in batteries, therefore there is a need for addressing the issue of sourcing and recovering them. The proposed new Batteries Regulations acknowledge the link between design, recyclability, and use of recycled materials (circularity), and also introduce the concept of extended producer responsibility, with phased obligations for the manufacturers.

Looking at the extra-European countries represented in BEST4Hy, it can be said that, overall, eco-design, use of recycled materials and recycling of fuel cells and hydrogen technologies is not focus of investment by the producers (with a known exception of Toyota) or the legislation. Producers are mostly concentrating on optimising the fuel cell system to reduce production costs. Only Toyota, which approaches car design looking at the whole life cycle, is known to be active in experimenting recycling of hydrogen storage and fuel cell. Unfortunately, information from Hyundai is currently not available. There is also some news of research being commissioned for recycling of large stationary hydrogen application, but the results are only preliminary and confidential.

It appears highly likely that cars with fuel cells will be treated similarly to cars with internal combustion motors as it is expected for electric vehicles. Specialised recycling treatment will be required for battery systems, and for fuel cells too, either driven by regulations or by economical interest (as it is the case for the catalysts in current cars, from which platinum is recovered).

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