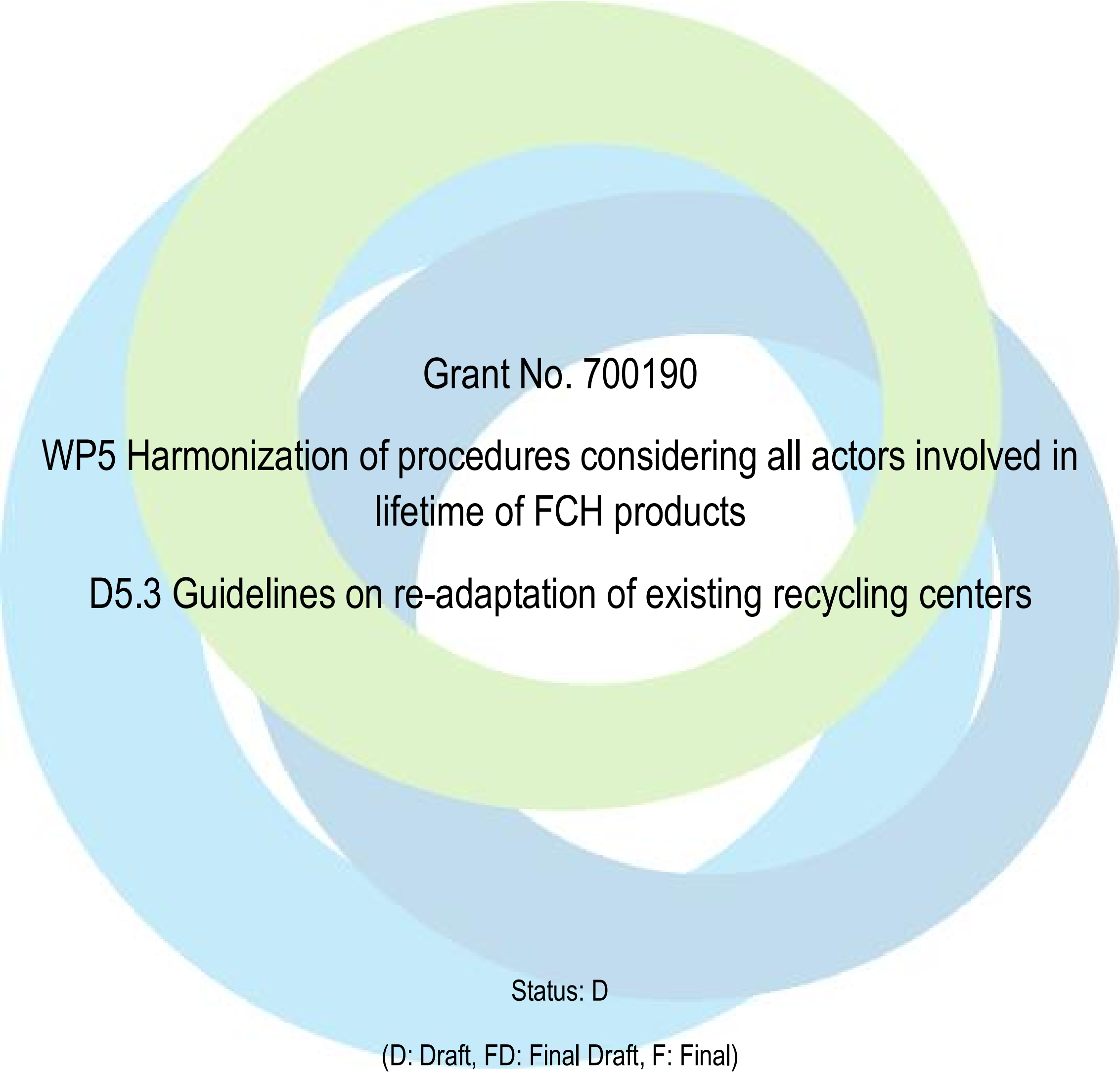
New technologies and strategies for fuel
cells and Hydrogen Technologies in the
phase of recycling and dismantling



Grant No. 700190

WP5 Harmonization of procedures considering all actors involved in lifetime of FCH products

D5.3 Guidelines on re-adaptation of existing recycling centers

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Executive Summary

As soon as fuel cell and hydrogen technologies are commercialized, the new recycling technologies, but also the new strategies in the phase of dismantling and recycling, studied in WP3, will involve changes in most of the existing recycling centres. Considering the example of ILSSA recycling centre and other cases, the layout and specific processes for massive recycling of PEMFCH technologies, SOFCH technologies, AWEs and PEMWEs will be proposed, detailing:

- New equipment/updating of existing machinery required for implementation of recycling technologies for FCH technologies.
- CAPEX and OPEX costs linked to re-adaptation.
- Economic feasibility study considering benefits from re-selling materials or components and re-using, repairing, remanufacturing, etc.

The scenario for this analysis will be 2030, considering estimations of FCH technologies penetration.

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Abbreviations

AD	Alcohol dissolution
AP	Acid Process
APU	Accelerated Processing Unit
AWE	Alkaline Water Electrolyser
BoP	Balance of Plant
CHP	Combined heat and power generation
EoL	End-of-Life
ERP	Extended Responsibility of the Producer
EU	European Union
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cell and Hydrogen
HDT	Hydrothermal technology
HMT	Hydro Metallurgical Technology
HS	Hydrogen Station
PCB	Printed Circuit Board
PEM	Polymer Electrolyte Membrane
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PEMWE	Polymer Electrolyte Membrane Water Electrolyser
PGM	Platinum Group Metals
PMT	Pyro Metallurgical Technology
RC	Recycling Centre
SED	Selective Electrochemical Dissolution
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SOFC	Solid Oxide Fuel Cell
TD	Transient Dissolution
WE	Water electrolizer
WEEE	Waste electrical and electronic equipment

1. Introduction

The Fuel Cell and Hydrogen (FCH) technologies will have in future a key role in the European energy sector, as well as in mobility and in building appliances. Advantages of hydrogen use are noted and many applications are practically available nowadays. However, an important feature that must be taken into consideration is the disposal at end-of-life: in a context in which environmental care and waste management are more and more important aspects, it is fundamental to consider not only a correct disposal of waste cells, but additionally a re-utilisation of materials for new FCH technologies production or for other purposes. The procedure of disposal and recycling will be performed by Recycling Centres (RC), provided the feasibility under bureaucratic and economic point of view and the adaptability to new technologies and chemical treatment of waste hydrogen technologies.

2. Scenario 2030: estimations of FCH technologies penetration

The development of FCH technologies is nowadays widely extended and well-known all over the world. From its very beginning, several applications have been the ones that have had the most important growth: use of hydrogen in transport, combined heat and power generation (CHP) for buildings and industry, production via electrolysis. The main visions and scenarios analysis detect hydrogen as a central pillar of the energy transformation, useful and crucial to contribute to the decarbonisation [1].

It is also necessary to underline that most of the FCHs applications are ready now, and in next years it’s foreseen a continuous growing in the market for the current applications.

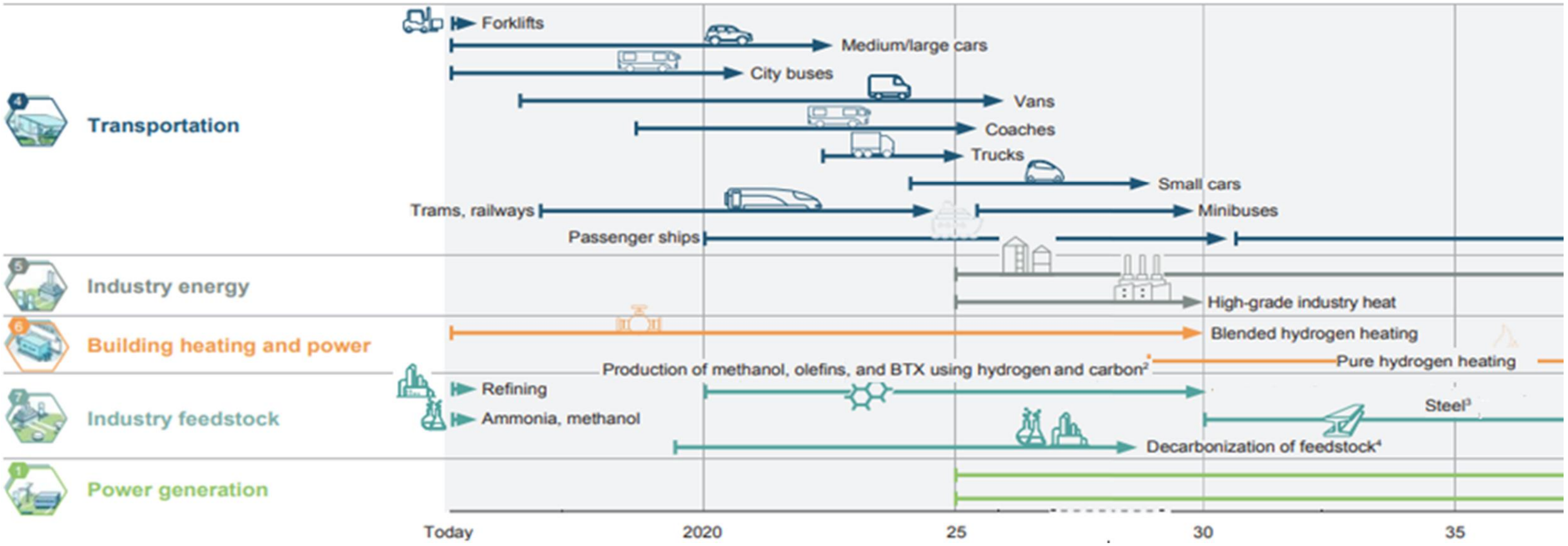


Figure 1. Hydrogen technologies deployment.

In **transportation**, hydrogen-powered vehicles are commercially available now or will become available in the next five years in medium-sized and large cars, buses, trucks, vans, trains, and forklifts.

In 2017 FCEVs running are more than 7,000 (passenger vehicles) so divided 3,531 running in U.S., 2,300 in Japan, more than 1,000 in EU (Germany and France are the countries with high numbers).

Toyota Mirai is the most sold FCEV in the world with more than 6000 units put on the road by the end of 2017. Further FCEVs are sold by Honda, Hyundai and Symbio.

More than 450 Fuel cell electric (FCEV) buses are on the road in North America, China, Japan and Europe. More than 15,000 fuel cell forklifts are operational in global warehouses, more than 300 hydrogen stations (HS) are in operation (92 in Japan).

The deployment of transport solutions has begun around the world, with Japan, South Korea, California, and Germany leading the way. Activities in other European countries, in the Northeast US, and in China are also under way.

- The Hydrogen Council, a group of 39 Companies working and promoting hydrogen economy, founded in Davos on January 7-2017, expects more than 400 million cars, 15-20 million trucks and 5 million buses in 2050. The milestones for 2030 are to reach globally 10-15 million cars and 500,000 trucks. In order to feed fleets of 10-15 million of FCEVs there will be the need of 15000 HS by 2030.
- The target in Japan is of 40,000 FCH vehicles by 2020; 200,000 by 2025 and 800,000 vehicles by 2030, in total. The Japanese Roadmap is also targeting 160 hydrogen stations by 2020 and 320 stations by 2025.
- The Korean Roadmap targets 10,000 FCEV and 100 stations by 2020; 100,000 vehicles and 210 HS by 2025; 630,000 vehicles and 520 stations by 2030. However, it plans to replace 26000 traditional buses with hydrogen fuel cells by 2030. Shanghai alone is planning to operate 3000 buses by 2020.
- Hydrogen Mobility Europe project is planning to place more than 1,400 fuel cell cars in customer hands and deploy 49 hydrogen stations across Europe until 2020. JIVE projects are planning to put 291 FC buses on the road by 2023. European target at 2025 is to reach the 747 hydrogen stations. The targets in France are between 20,000 to 50,000 FCEVs by 2028 and near to 1,000 HS. Germany targets are 1,000 HS by 2030.
- China’s Technology and Industrial Development Strategy has the goal to build more than 100 hydrogen stations by 2020, 300 stations by 2025 and 500 stations by 2030. 5,000 fuel cell vehicles are planned for demonstration in 2020, 50,000 vehicles in service in 2025 and over 1,000,000 fuel cell vehicles in service in 2030.
- California Air Resources Board projects a total of 13,400 FCEVs in California by 2020 and 37,400 by 2023. 94 stations are anticipated by the end of 2023 [1, 2].

Fuel cell technology in buildings is another active sector. CHP stationary fuel cells penetration is expected to reach the 12,000 units by 2020, 42,000 units by 2030, 178,000 units by 2040 and 200,000 units by 2050 in the conservative scenario, and 21,000 units by 2020, 68,000 units by 2030, 882,000 units by 2040 and 1,676,000 units by 2050 in the high pathway scenario [3] both in the European frame. Additionally, the ENE-FARM project has predicted 389,491 shipments by 2020 in Japan [4]. Based on that data, the market will reach 1,986,238 units shipped by 2050 in the conservative scenario and 2,635,755 units in the optimistic one [5].

The ene.field [6] project demonstrated 1,046 units in real customer homes, with more than 5,5 million hours of reliable operation, generating in excess of 4.5 GWh of electricity. Following ene.field, PACE [7], a five-year project, will deploy more than 2,500 of the next generation Fuel Cell micro-CHP units in 11 European countries by 2021.

An important niche market appears for fuel cells is the telecommunication applications, specifically in the telecommunication base stations, where 5,000,000 units will be installed by 2020 [8], considering a 50 % fuel cell penetration in an optimistic scenario and a 5 % in the conservative one, 2,500,000 and 250,000 FC telecom base stations will be replaced by 2020. When talking about Auxiliar Power Units (APU); 13, 996 units are expected to be reached by 2020; 25,436 by 2030; 36,924 by 2040 and 48,412 by 2050 in the conservative scenario and 23,643 by 2020; 65,666 by 2030; 127,525 by 2040 and 208,430 by 2050 in the optimistic scenario.

If we sum up the European market status today, more than 1,000 FCEVs and 68 FC buses are running and 126 HSs are installed. Related to CHP systems, with ene.field 1,000 units are running now in Europe.

The picture below reports the vision of Hydrogen Council for the hydrogen economy in 2030 and 2050 divided for the main sectors.

SECTOR	2030 SCENARIO	2050 SCENARIO
TRANSPORT	1 in 12 cars sold in California, Germany, Japan, and South Korea could be powered by hydrogen, more than 350,000 hydrogen trucks could be transporting goods, and thousands of trains and passenger ships could be transporting people without carbon and local emissions.	Up to 400 million passenger vehicles (~25%), 5 million trucks (~30%), and more than 15 million buses (~25%) running on hydrogen
	Globally 10 to 15 million cars and 500,000 trucks will be powered by hydrogen	20% of today's diesel trains replaced with hydrogen- powered trains
	Deployment of H2-powered trains and passenger ships will start.	20 million barrels of oil replaced per day, 3.2 Gt CO2 abated per year
Industry energy	One in ten steel and chemical plants in Europe, North America, and Japan uses hydrogen for low-carbon production	12% of global industry energy demand (16 EJ) met with hydrogen – 23% of high-grade, 8% of medium-grade, and 4% of low-grade heat and power
	4 million tons (0.6 EJ) additional hydrogen used	~1 Gt CO2 abated per year
Building	The equivalent of 6.5 million households heated with blended or pure hydrogen using about 3.5 million tons (0.5 EJ) of hydrogen	8% of global building energy use for heat and power (11 EJ) provided by hydrogen
	10% of users connected to the hydrogennatural gas grid using fuel cell combined heat and power units (micro-CHPs)	About 700 Mt CO2 abated per year
Industry feedstock	Steel plants pioneering zero-carbon iron making using hydrogen reduction (using about 100,000 tons hydrogen)	10% of crude steel production, about 200 million tons, based on hydrogen, saving 190 million tons of CO2 per year
	10 to 15 million tons of methanol and derivatives, such as olefins and aromatics, produced from clean hydrogen and carbon (using about 2.5 million tons hydrogen)	30% of methanol and ethanol derivatives produced through hydrogen and carbon, recycling 360 million tons of CO2 per year
	Demonstration of clean hydrogen use in chemicals and refining industries	Existing feedstock uses for chemicals and refining industry decarbonized, saving 440 million tons of CO2 per year
Energy system	250 to 300 TWh of excess solar and wind electricity converted to hydrogen	500 TWh of excess solar and wind electricity converted to 1.5 EJ hydrogen
	More than 20 power plants generating 100 to 200 TWh of dispatchable power from clean hydrogen	1,500 TWh of dispatchable power produced from 9 EJ clean hydrogen
	More than 10 ships transporting a total of about 100,000 tons hydrogen per year	55 million tons of hydrogen, or 8 EJ, transported/ shipped overseas
	200 TWh hydrogen stored in underground salt caverns	3,000 TWh of hydrogen, or 18 EJ (worth 55 days of wind, solar, and hydrogen demand) stored in strategic reserves

Table 1. FCHs 2030 and 2050 scenarios for different sectors

3. Re-adaptation of recycling centres for implementation of new processes

It is necessary underline that most FCHs applications are yet ready now, so in a short scenario what mainly emerged, also from the two Workshops organized along HYTECHCYCLING project, is that:

- ☐ 50% of the Recycling Centres (RC) have the technology required for FCH's recovery.
    - Whereas, 66% has pyro-hydrometallurgical and 34% hydrometallurgical processes.
- ☐ 60% think about investing in technology for recycling FCH.
    - Whereas, for the other 40%, it will depend on the market potential and the method employed.
- ☐ 84% of RC questioned have no reluctance in treating any material that composed FCH technologies.
- ☐ 40% thinks that the components should be distributed between specialized centres.

It's a good starting point, mainly as many recycling centres are concerned with the recovery of precious metal from automobile sector (for instance, it is possible to understand which are the quantities of Pt per cells that marks an economically advantage in order to recover Pt).

There are some aspects that a RC must take into consideration in order to re-adapt it for FCH technologies.

- Make a proper analysis in materials composition of waste cells, in order to study properly the mass balance; next, identify the technologies that can mechanically separate the different materials and study the cost for such procedures.

- The revenues of this technology will be analyzed by an economic and financial study and compared with all the identified and possible technologies. Finally the technology will be selected according to criteria of efficiency, performance and quality of the materials that can be obtained from the processes of each technology.

- At the same time, a market study has to be carried out to identify the potential customers receiving the materials produced, establishing the technical specifications that require the material (weight, granulometry, format, packaging, etc.) and the price they are willing to pay for it.

With all this information, the technology to be used is determined and its costs and the income that will be generated with the treatment of the new waste are analyzed.

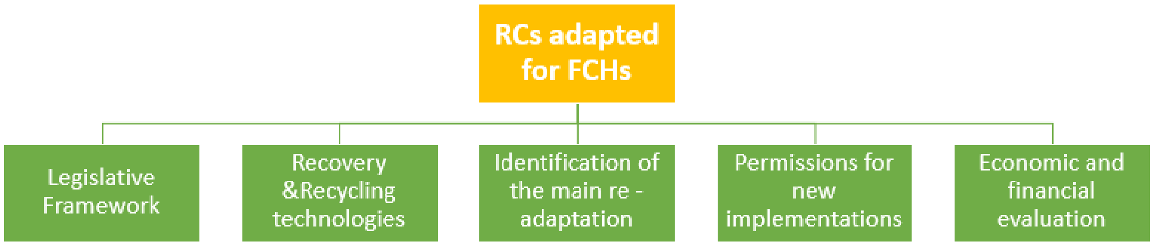


Figure 2. Steps a RC has to follow to re-adaptation for FCH technologies waste

First of all, RCs will have to deal with all existing Regulations concerning FCH utilization and especially their disposal at end-of-life; next, they will focus on available technologies for the correct recovery of all materials composing a single cell, and on the main possible re-adaptations of each component divided (e.g. if it could be completely recyclable or not) and to apply to the already existing RC structures for those applications. Finally, after a consequent study on permissions for the new implementations, the feasibility of these procedures must be assessed through an economic and financial analysis.

3.1 Legislative Framework related to FCHs

The first aspect a RC has to take in consideration in a new approach to fuel cell systems treatment is to detect the main EU legislations comply with FCH systems. The deliverable *D2.3 Regulatory framework analysis and barriers identification [9]* reports a good analysis of existing ones comply with FCHs.

The report analyses the legislation on the material design and the end-of-life mainly related to fuel cell and hydrogen systems, so specific Directives are reported and related to each part of the FCH system:

- Eco-Design Directive has to be considered in the whole FCHs system design, but also for the materials selection both FC stack that 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.

However, the deliverable D2.4 [10] reports also the main barriers linked with existing regulations:

- 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 a negative impact of the product. Another fundamental aspect tied to eco design is related to the choice of materials during the design phase, it can impact positively on the cost of technology. Barrier related to 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 manufactures to take into serious consideration this requirement because it might preclude the marketing of these systems. Barriers related to REACH Regulation and RoHS Directive
- Barrier on end of life management: recycling target could be too restrictive if the FCH developers will not put attention on them during the design phase and this could affect the technology's image. Barrier related to ELV Directive. 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 in order to limit landfill waste and following recovery and recycling procedures taking them into account during the eco design phase [11].
- Lack of a specific FCH Directive. Some current Directives include FCH products or have to be taken into account with a FCH system, but the creation of a more detailed FCH relevant regulatory is needed.

A Recycling Centre can overcome the barriers on Eco-design regulation via:

- Specific agreements with manufacturers: profitability and new markets.
- Developing a more environmental friendly method of recycling.
- Developing a more detailed research recycling methods.

- Guaranteeing the highest recycling ratio possible.
- Guaranteeing the origin of the material.

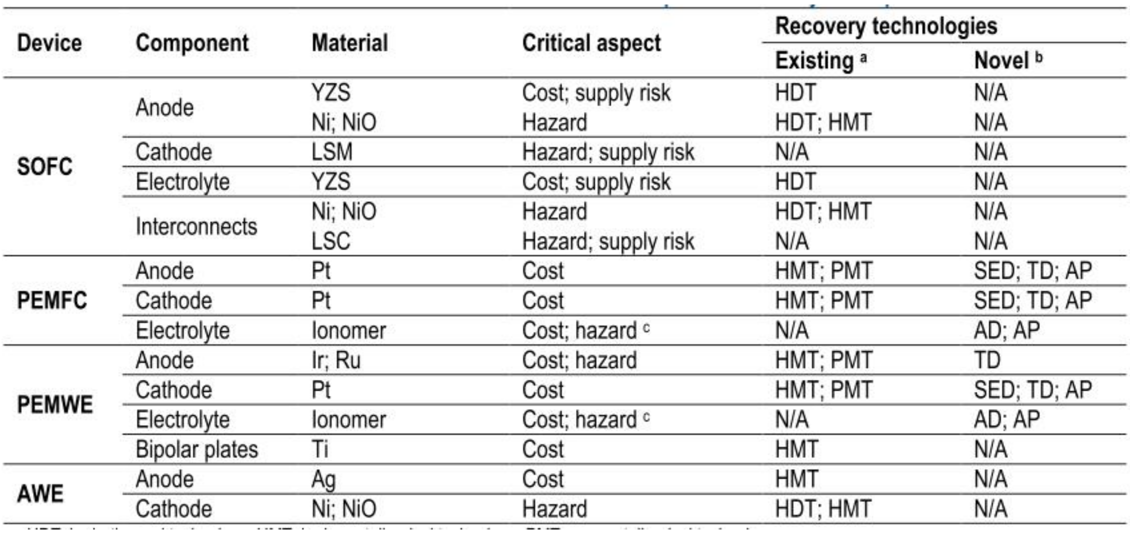
Consequently, according to the type of material treatment in which the RC is specialised, there will be necessary to rely on one of those specific legislative and agreements aspects.

3.2 Recovery and recycling technologies

The second aspect a RC has to take in consideration is the evaluation of existing and new strategies related to recycle FCH technologies.

The two reports *D2.2 Existing end-of-life technologies applicable [12] to FCH products* and *D3.1 New end-of-life technologies applicable to FCH products* [13] contain the main inputs for a RCs that decide to implement new strategies and technologies for dismantling and recycling FCHs.

Table below summarizes the existing and novel recovery technologies applicable to critical materials of FCH stacks: the existing technologies for PEMFCs, PEMWEs, AWEs and SOs are focused mainly on hydrometallurgical and pyrometallurgical recovery of precious metals used in the stacks as catalysts for the conversion process.



Device	Component	Material	Critical aspect	Recovery technologies	
				Existing [a]	Novel [b]
SOFC	Anode	YZS	Cost; supply risk	HDT	N/A
		Ni; NiO	Hazard	HDT; HMT	N/A
	Cathode	LSM	Hazard; supply risk	N/A	N/A
	Electrolyte	YZS	Cost; supply risk	HDT	N/A
	Interconnects	Ni; NiO	Hazard	HDT; HMT	N/A
		LSC	Hazard; supply risk	N/A	N/A
PEMFC	Anode	Pt	Cost	HMT; PMT	SED; TD; AP
	Cathode	Pt	Cost	HMT; PMT	SED; TD; AP
	Electrolyte	Ionomer	Cost; hazard [c]	N/A	AD; AP
PEMWE	Anode	Ir; Ru	Cost; hazard	HMT; PMT	TD
	Cathode	Pt	Cost	HMT; PMT	SED; TD; AP
	Electrolyte	Ionomer	Cost; hazard [c]	N/A	AD; AP
	Bipolar plates	Ti	Cost	HMT	N/A
AWE	Anode	Ag	Cost	HMT	N/A
	Cathode	Ni; NiO	Hazard	HDT; HMT	N/A

Table 2. List of critical materials for FCH stacks and recovery techniques (existing and novel). HDT: Hydro Treatment, HMT: Hydro Metallurgical Technology, PMT: Pyro Metallurgical Technology, SED: Selective electrochemical dissolution, AD: Alcohol dissolution, AP: Acid process, TD: transient dissolution [13].

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The main conclusions related to FCH stacks recovery material that come from the analysis are that:

- Novel EoL technologies for FCH stack materials are mainly oriented towards the recovery of precious metals. When compared to conventional EoL technologies, the main advantages associated with the reviewed emerging technologies are related to the possibility of recovering more than one valuable product (ionomer or carbon support for PEM-based systems) in addition to the precious metals.

- Furthermore, novel technologies are usually linked to enhanced technical performances (e.g., in terms of process duration), improved economic and environmental performances (thanks to the lower amount of energy required), and safer working conditions (thanks to mild operating conditions in terms of temperature, pH and voltage, as well as to the use of non-hazardous reactants).

- When compared to conventional EoL technologies such as pyrometallurgical processes, TD generally shows a more favourable profile with relevant advantages in terms of versatility and economic performance. SED and AD could also be considered promising EoL technologies, but their application is highly conditioned by the actual commercial deployment of PEM devices. In this sense, and in order to effectively face the challenge of a well-established hydrogen economy, a full EoL strategy beyond the technology level is still required.

BoPs recovery is focused on their re-conditioning and reuse of them in new products:

- Regarding BoP components, novel technologies are found to be applicable mainly to PCBs, which are rich in high-value metals and for which current recovery practices lead to significant environmental concerns. Although several emerging technologies could be applied, further research is still needed due to the low level of industrialisation. In general, the main trend for BoP components is oriented towards the reuse of components such as pumps, blowers, compressors, etc. Nevertheless, an important drawback is the evaluation of lifetime of the single element: for such applications, instead of focusing on recycling, it would be better to do preventive maintenance and use components for lower requirements applications.

3.3 Identification of the main re-adaptation

Figure below shows the overall EoL scheme applicable to PEMFC, PEMWE, SOFC and AWE devices, as reported in D3.1 [13].

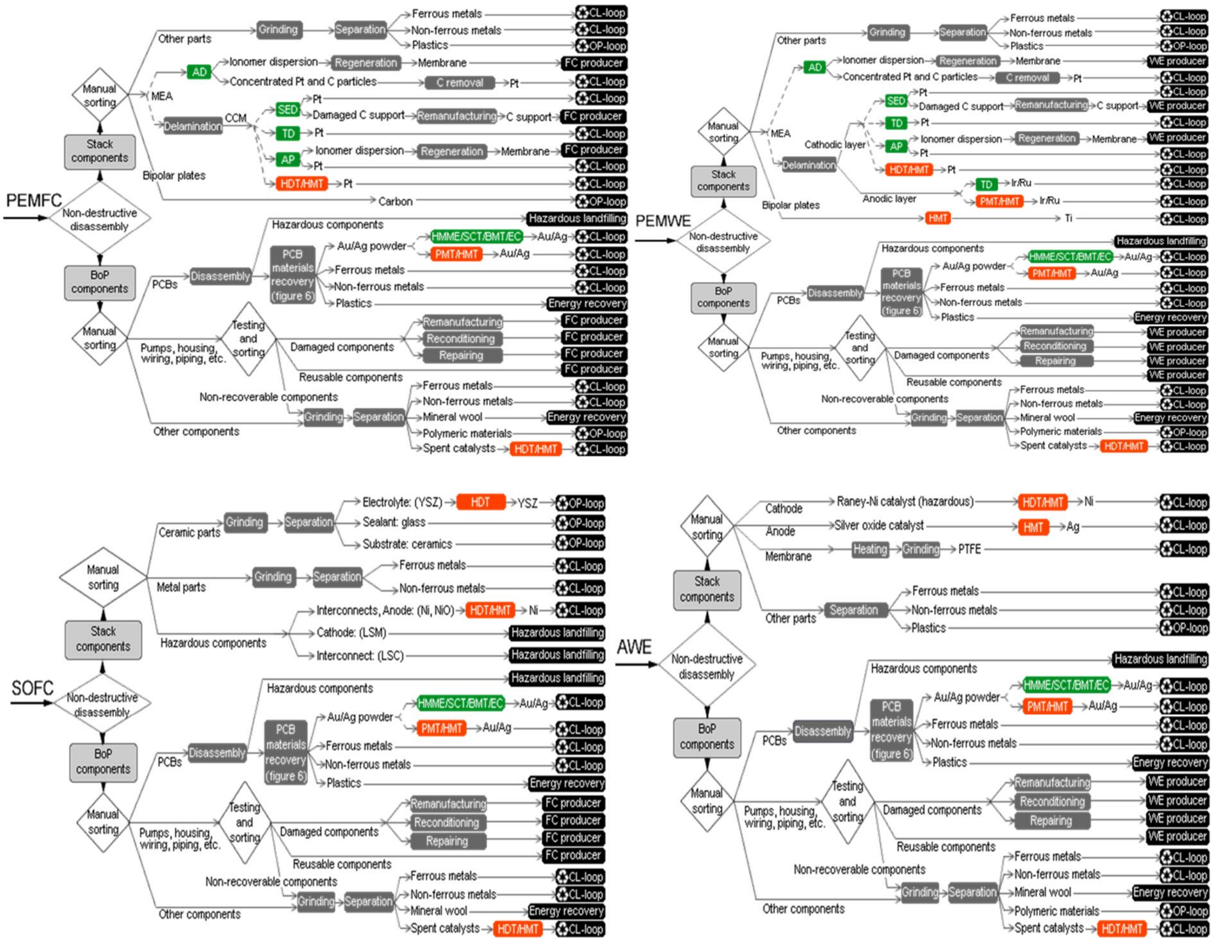

Figure 3. Overall EoL strategy at the technology level for PEMFC, PEMWE, SOFC and AWE [13].

The process of recycling includes:

1. Collecting or gathering waste material that can be re- processed.
2. Delivery to recycling plant.
3. Sorting (mainly manually) and disassembly.
4. Processing by means of shredding, grinding, rinsing, using the reprocessed material (instead of using virgin material) combined with other materials to manufacture new products.
5. Processing with chemical treatment (existing and/or novel technologies).
6. Selling the products back to the consumers (new or original ones).
7. Selling or sending back through specific agreement the material to FCH producers.

The first two steps of the recycling process are responsibility of FCH technologies manufacturers, that will manage damaged stacks by end users/clients and internally will perform a first integrity analysis, substitution of single cells (when possible). All the materials that are not recoverable will be directed to the recycling. The ERP will be also maintained if the recycling center won't receive the technology itself, but it is able to make the FCH equipment arrived to the RC and cover the costs.

Looking the overall EoL strategy at technology level for all the FCHs (Figure 3), the FCH technologies received will be disassembled in RCs by a manual separation of the different components. After this, and a manual sorting stage, the different pieces will be into shredding, separation, milling, and other processes that will cause that the FCH technology will be split into small scrap pieces. All this pieces will be sorted by means of magnetic separation, optical separation and more processes.

It is necessary to underline that the steps 3 and 4 will be the same for each FCHs technologies treated in a RC and existing RCs have yet mechanical equipment.

After the stages 3 and 4, the heart of the recycling strategy mainly linked with FCHs is the chemical process:

- existing ones
    - hydrometallurgical, (HMT)
    - pyro-hydrometallurgical (PMT)
- or novel processes
    - Alcohol dissolution (AD)
    - Acid process (AP)
    - Selective electromechanical dissolution (SED)
    - Transient dissolution (TD)

The current recycling centers are able to introduce the amount of equipment that will be recycled in the short to medium term without the necessity of neither new tools nor additional space, nevertheless, this document aims to presents which should be the process in order to introduce a new activity as the FCH technologies recycling.

The main sectors in a RC are here reported: reception of the materials, storage and separation, disassembly zone, chemical treatment zone, grinding zone, final storage and expenditures. The Figure below reports an example of layout of a RC.

Mainly all the zones are linked and it is possible to avoid intermediate stages when they are not needed. This structure could be similar to the batteries and the WEEEs recycling centers. Size and dimensions of the reception of the materials, storage and separation differ on the base of scale of equipment's treated (small, medium and big scale).

The *D6.1 Business Model* [14] presents a good vision on the collection of different scale equipment, but mainly HyTechCycling proposal focus is the medium scale FCH technologies.

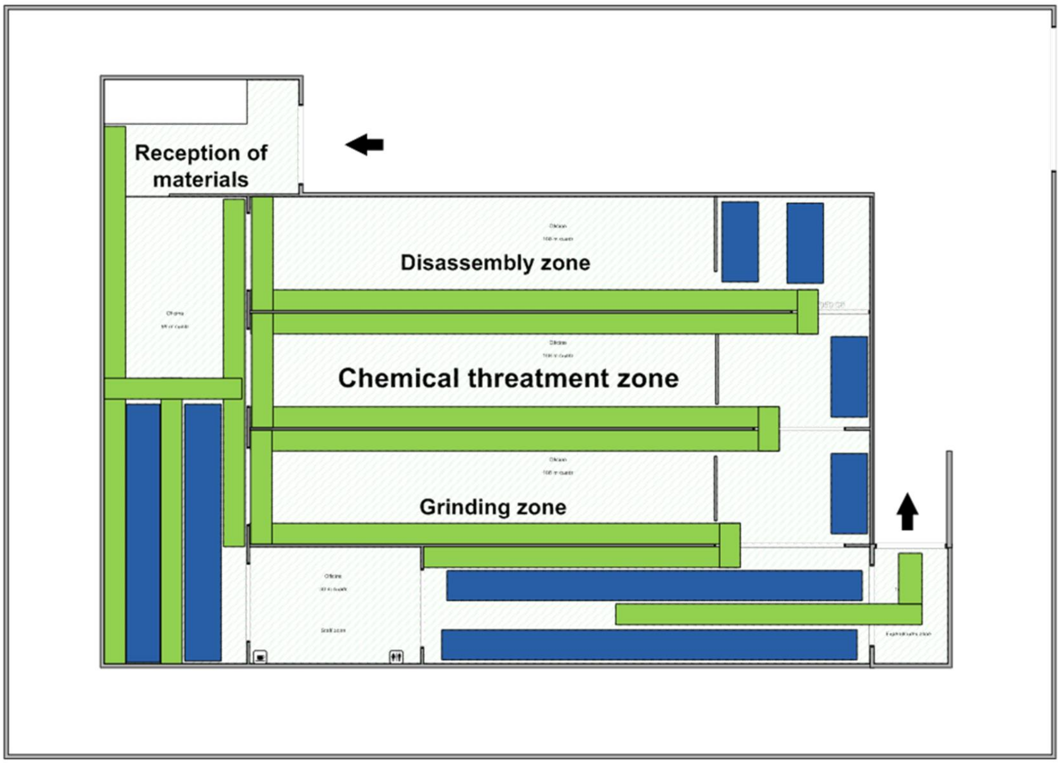

Figure 4. Layout of a recycling centre.

Starting from the consideration above, the main re-adaptations of a current RC that will approach to FCHs recycling are linked to the chemical processes: for the recycling of this waste RCs should invest in new equipment, facilities and machinery / staff training, if new processes are going to be implemented.

In order to show a real example, it is possible to study the ILSSA example with its mechanical equipment: fragmentator, chopper, shredder, granulators, aspirators, separation table, water separation table, Foucault and overband magnet, density machines.] They are able to retrieve e.g. various fraction of Ferrous and SS (Stainless Steel), various fraction of non-ferrous metals (Aluminium, Copper, Brass and Printed Circuit Boards (PCB's)), refining material containing e.g. Copper, Brass, Zinc, Lead and Precious Metals (PM), organic fraction with e.g. plastic, rubber, wood, textile and dust.

The most important task for a company that wants to convert its production is to review the fundamental situation and make a preliminary risk assessment. This preliminary assessment can be done by a designated manufacturing expert who also designs the new process. The initial evaluation must consider many restrictions as conditions of the place, the existing technological processes, plant configuration, the level of production and the use of capacity, budget constraints dictated by the cost-effective of the new technology, availability of qualified personnel and material. The testing and compliance with standards and regulations are a critical part of all change. Special consideration should be given to the design and installation of the production and areas associated with the management of hazardous waste for the environment and the health of people.

3.4 Permissions for new implementations

The third aspect linked to the availability to re-adapt recycling centres to FCH technologies' treatment is the evaluation of permissions and authorizations needed.

The main aspects to take in consideration with new implementations of existing plants/re-adaptation are that for new recycling processes implementation it's necessary to obtain a new authorization (procedure which requires lot of time).

So, the main problems that will incur with new recycling processes implementation are mainly linked with the bureaucratic aspects, request of authorization and who to submit, it depends on the type of residue that must be treated and it is strictly connected with the legislation that is not currently specific to fuel cell systems.

The first problem therefore is not technological but administrative and legislative. In general, any re-adaptation of RC depends on the type and size of the modification, if it exceeds 25% of the amount of generation of waste, or new emissions to the environment occur, a new authorization is required.

Furthermore, the residue must be mapped and its identification unified in all member states. The non-correct identification of the type of waste, in this case also connected by a suitability of suitable legislation, can lengthen the time required for obtaining the authorization. Similar residues can be treated according to different processes, so the correct identification is fundamental.

Furthermore, after having treated an end-of-life product, the important aspect is the percentage of the residual derived from the treatment and how efficient and productive it is for the recycler. This aspect must be very clear to the producer, since the product and so the product's residue is the extended responsibility of the producer and define how much can be recovered by a product.

Already existing recycling centres may well perform part of the job (. as far as stocking is concerned), but since the recovery of this kind of products is quite complex and involves many different steps, some centres will have to extend their present requirements,

Already existing recycling centres may well perform part of the job (f.i. as far as stocking is concerned), but since the recovery of this kind of products is quite complex and involves many different steps, some centres will have to extend their present requirements, to define what centre is working with PGM materials and if it is interested in recovery or not. Otherwise, the RCs could simply store the PGM materials and send them to other centres operative in such recycling modes.

In general, a RC has to request a new authorization: in Spain it has to be required to the regional Government but in other countries can be other level of Government. The time to obtain permissions differs from Country to Country, but European government is encouraging that it be similar in all the countries of the EU.

3.5 Economic and financial evaluation

The fourth aspect is the economical evaluation. A RC has to perform a financial model to determine the financial implications and viability of the recycling process.

The financial model that a RC has to approach will evaluate the process over 5 years, starting from 2020.
The calculation will include:

3.5.1 Input costs for new plants

	INPUT data	comments	comments
COSTS	CAPEX	cost of the new plants investment, depreciable over 10 years	COSTS LINKED TO NEW PLANT INVESTMENT AND INSTALLATION
	Plant assembly	costs for installation of the new plants	
	Civil works and area arrangement	amortization for the duration of the BP (20 years)	
	Technical expenses	operation management, engineering, testing, safety, supervision	
	Insurance		
	Extraordinary maintenance	ex. Substitution of parts	COSTS OF OPERATION OF PLANT
	Ordinary maintenance	mainly 3% of CAPEX	
	Operating costs	Electricity, Consumable goods	
	Acceptance costs of the waste	if needed, as expressed before some zones are yet present in a RC	FIXED COSTS primarily took the form of labour
	Personnel for plant management	if needed new personal	
	Overheads	1 person, calculated % of total revenue	
	Land ownership tax	if there is the need of new land	

Table 3. Input costs for new FCHs RC plants

Below and in the Table 3 are summarized the main costs a RC has to sustain for the new installation or apartment of the existing ones:

- Investment costs of new plants, can be considered to be amortized over 10 years
- Plant assembly: costs linked with the installation of new plants
- Civil works and area arrangement: depreciated for the duration of the Business Plan (20 years)
- Technical expenses, linked with the installation of new plants and include: operation management, engineering, testing, safety, supervision
- Insurance: needed for new plants acquisition
- Extraordinary maintenance: include evaluation of some parts that have to be substituted during the plant life
- Ordinary maintenance: in general 3% of the value of the CAPEX.
- Operating costs: electricity, consumable goods ex. fuel oil, water, etc.
- Acceptance waste costs: these costs are yet present in a RC, they can include operating costs for waste acceptance activities + external management with respect to pure plant management.
- Personnel for plant management: if there is the need of new personnel/staff totally dedicated to the new plants
- Land property tax: if there is the need of new land
- Overheads: calculated as a % of total revenue

Analysing the investment costs to implement the industrial reconversion of the plant it is possible to both financing options: purchasing or renting.

Either the RC spends all the money at once (purchasing) or the RC pays a monthly rent for that good (renting). The purchasing option assumes that the recycling centre has the necessary financial resources at the beginning and that it will not use them for other purposes. This investment must be provided with the corresponding provisions to acquire a good equivalent after the useful life of the industrial good.

The renting option assumes, on the contrary, that the RC pays a monthly fee for the acquired good. That fee can be divided into a monthly fee paid to the supplier of the good and another paid to a financial entity that finance the purchase.

To decide how to acquire an industrial good, the first thing to compare is the total price of acquisition of that good (Total Cost of Ownership). The second thing to assess is whether the provider of the good is able or not to provide a service in exchange for a monthly fee. The renting acquisition option mainly targets suppliers that have transformed their business into a service rather than the manufacturing of an industrial good.

If the technology to recycle these new wastes is very specific, there will be no option to finance through renting.

3.5.2 Bank financing

In general also a financing hypothesis is considered, where % Equity and Equity Value are the shares of the firm's own equity in total financing, Debt is the part that will be financed, with a Return Calculated in Years at a constant Interest Rate.

	input data	unit	value	comments
Bank financing	equity	%	40%	
	interest rate	%	5%	
	repayment of mortgage debt	years	10	
	estimate annual inflation rate	%	1%	
	Estimate of plant degradation	%	1%	starting from the 5th year (estimate between 1-2%)

Table 4. Example of bank financing hypothesis for new FCHs RC plants (Information raised from industrial experts)

3.5.3 Revenues

The economic feasibility study must also consider the benefits that the RC will derive from the new market on FCHs. The analysis will start from a theoretical mass balance of the materials that make up the waste and considering the main valorization of new products recovered.

As reported in Figure 3, there are different outputs/revenues from FCHs recycling process:

- Revenue from closed loop recycling products.
- Revenue from open loop recycling products.
- Revenue from Recycled Material transfer to FC or WE producers (after regeneration/reconditioning/remanufacturing).
- Revenue to Energy recovery.

Closed-loop recycling indicates a product can be recycled back into the same application, while open-loop recycling (down cycling) indicates that it can be recycled into other types of products.

Some examples: reutilization as spare parts in other fields for components of the FCH technologies; power Electronics that could be re-used: universities, technician trainings, lower requirements of power electronics.

Finally, all these materials could be scrap which after treated can be sold obtaining profits, and following the structure that the recycling centers follows today.

The reintroduction of the recovery of pieces and materials has been identified as a good way to decrease the size of new materials.

If the recycling centre will obtain profits from the process and the commercialization of the materials, it may participate economically of the cost coverage. This is the objective of the RC economic evaluation for new technologies: the materials are recycled, maximising the circularity and promoting agreements mainly with FC/WE manufacturers in order to return them the materials.

4. Conclusions

At this point, it’s practically impossible to think about Fuel Cells and Hydrogen Technologies production and exploitation without looking after their end-of-life: the concept of “Circular Economy” is slowly getting a foothold, creating both in constructors and users the idea of make products re-usable for a collective benefit and advantage. As many other applications, also waste hydrogen technologies can be recycled, by sorting and dividing them in main constituent materials and giving them a second life; under proper legislative and economic conditions, many Recycle Centres are available to meet the goal, investing in new technologies and applications.

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