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

Grant No. 700190

WP6 New business model and implementation roadmap

D6.1 New business model

Status: F

(D: Draft, FD: Final Draft, F: Final)

Dissemination level: PU

(PU: Public, CO: Confidential, only for members of the consortium (including the Commission Services))

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 700190. This Joint Undertaking (JU) receives support from the European Union's Horizon 2020 research and innovation programme and Spain, Italy, Slovenia.

Document Change Control

Version Number	Date of issue	Author(s)	Brief description of changes
01		A Bernad, M.Liendo	First draft of the document

Executive Summary

According to the future perspectives of the hydrogen economy, Fuel Cell and Hydrogen (FCH) technologies will become a key technology in a clean and emission-free future. These equipment, even if are a clean energy solution, should be considered also from the product perspective and its End of Life (EoL).

FCH technologies will have to be recycled in the future and the market should be ready for this new product. For this reason, the current document aims to set the basis for the EoL management in the future. The business model aims to consider all the actors and the needs that they may have in this area.

As far as the document presents, the current recycling centres may be able to cover the recycling of the FCH technologies with minor changes.

The recycling market will go from thousand € to millions depending on technology, the logistic and also other possible costs. A first iteration of the optimization of the business model is performed and presented. Indicators such as the total costs, the achievement of recycling targets or the end-users involvement have been identified. In addition, the different barriers and risks for the recycling chain are also detailed.

The final objective of this document is to present how the business model should be for the different technologies considered under the umbrella of the HyTechCycling project and who should cover the costs and why.

Contents

List of Figures

List of Tables

Abbreviations

AWE	Alkaline Water Electolyser
BAT	Best Available Technologies
BoP	Balance-of-Plant
DIFT	Do It For Themselves
EoL	End-of-Life
EPR	Extended Producer Responsibility
EU	European Union
FCH	Fuel Cell and Hydrogen
KPI	Performance Indicators
kW	kilo Watts
MW	Mega Watts
OECD	Organization for Economic Co-operation and Development
PEMFC	Polymer Exchange Membrane Fuel Cell
PEMWE	Polymer Exchange Membrane Water Electrolyser
PESTLE	Political, Economical, Social, Technological, Legal and Environmental Analysis
PET	Polyethylene terephthalate
PGC	Platinum Group Components
PRO	Producer Responsibility Organisation
PV	Photovoltaic
SOFC	Solid Oxide Fuel Cells
WEEE	Waste of Electrical and Electronic Equipment

1. Different time lapses needs for different approaches.

As other products as smartphones, aeroplanes or batteries, the EoL of any product has to be adapted to the status and market where the original product has been introduced. Today, FCH technologies are an emerging market. The current market is expected to grow in the near future, as hydrogen is one of the ways of integrating more renewable energy in the energy markets, action in line with the objectives of 2030 of the European Union (EU). [1]

1.1 Trends for the future

The recycling strategy and its evolution are related directly with the volume of FCH equipment to recycle in the market. In order to estimate how the trend followed, it becomes necessary to understand when the markets will increase its size.

Moreover, the trend for the introduction of the equipment in the reuse and recycling chain will suffer for a time delay, because once the equipment has been sold, the recycling process will start at the end of the expected useful life.

FCH technologies are an investment and thanks to it, the equipment will be used until the moment the equipment is not able to operate. To adapt the business model to the real world, information raised from manufacturers have been used to obtain the expected useful life of the different technologies that fall under the study of this business model (Alkaline Water Electrolyser (AWE), Polymer Exchange Membrane Water Electrolyser (PEMWE), Polymer Exchange Membrane Fuel Cell (PEMFC) and Solid Oxide Fuel Cell (SOFC)) and the expected evaluation of this parameter.

In order to present a sensibility analysis, different trends and roadmaps have been considered [2], [3] The business model time frame has been set considering the year 2025 as the beginning and ending in 2050.

Figure 1 presents the annual demand of hydrogen and as equivalence, 1 EJ is provided by 7 million tons or 78 billion cubic meters of gaseous hydrogen and it is equivalent to 278 TWh of electricity.

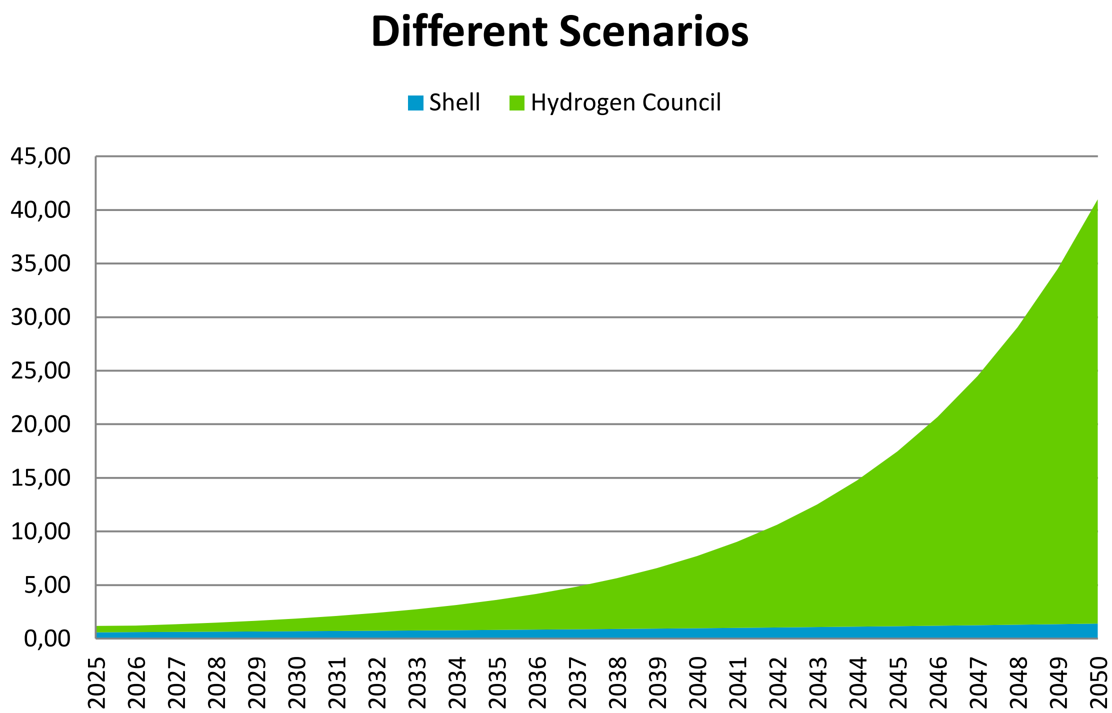


Figure 1. Trends of market evolution per scenario. Source: [2], [3]

In order to analyse these scenarios, all of them has been put in the same condition. As a result, in some scenarios, the hydrogen demand that will go towards the industry from Steam Methane Reforming (SMR) has been eliminated, as far as SMR will still be a way to produce hydrogen, but this production does not affect to the FCH technologies business model.

Another assumption that has been considered in the frame of this business model is based on the fact that all the hydrogen that will be produced by electrolysis will be used in its final stage by fuel cells.

In addition to these assumptions, both scenarios are defined from the global perspective meanwhile this business model is focussed in the EU and its countries. Due to it, a correction has been done. the different countries, they have been classified according to the tiers definition used in the HyLaw project[1] in order to establish also the differences between them [4].

The **European perspective** will assume less recycling centres able to recycle the FCH technologies, causing higher volumes to recycle for the recycling centre and higher logistic cost related to transport and collection. The **national perspective** assumes that in each country there will be centres able to recycle the waste, reducing thus the distances and the volume recycled.

Moreover, all technologies will coexist in the future and the evolution of market share differs and evolves in a different way for each technology. To estimate this evolution, and after consulting the manufacturers, it has been decided to split the growth of the technologies, giving to each one of them, a percentage of the market share that evolves annually.

[1] The HyLAW project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No 737977. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research

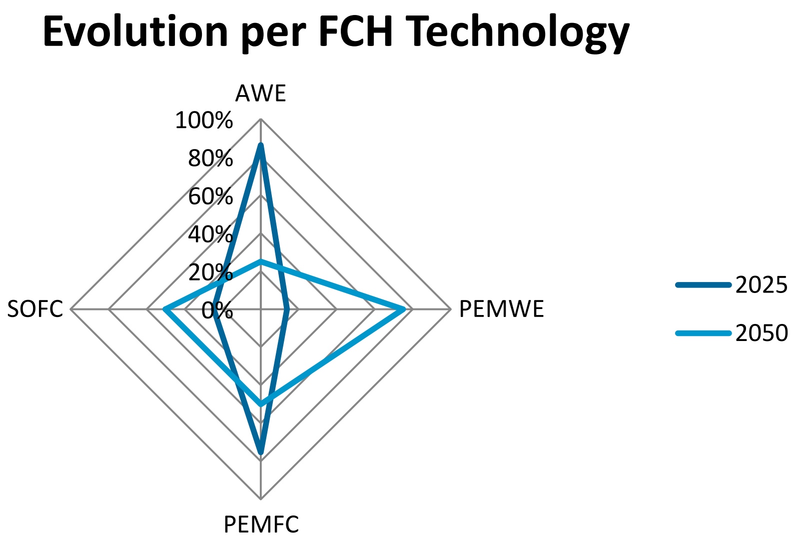


Figure 2. Market shares evolution. Source: Manufacturers information

According to the previously presented information, the development and the creation of a business model which will be able to evolve and to adapt to the future situation is needed. At the same time, the business model should achieves high recovery and recycling values for the current technologies which are put into the market.

1.2 Actors and relationships in the whole lifecycle

Summing up information raised by this project in previous publications, the industrial actors related to the EoL have been determined [5]. As it has been presented, the optimum target for this system is to maintain as much as possible the closed loops[2] in the recycling strategy. Actors that may be involved in the EoL, by acting in the recycling, in the manufacturing, or in the use and the relationships among all the actors are presented in Figure 3.

[2] A closed loop means that the recycled or reused material could be used again in the FCH market; meanwhile, the open loop means works with the materials that are not able to be reintroduced in the same market again.

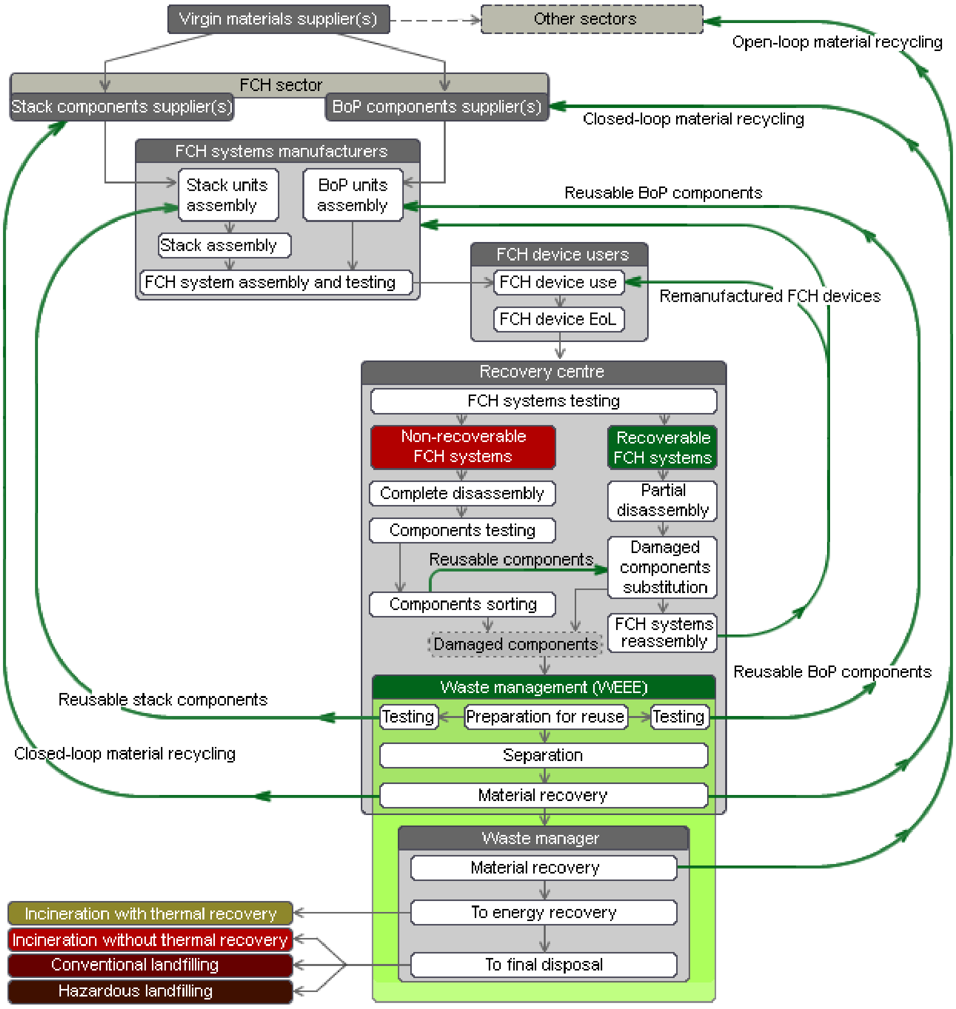


Figure 3. The lifecycle of a FCH technology. Source: [5]

Nevertheless, the business model is influenced by other actors as end-users or Producer Responsibility Organisations (PRO) if exists. These actors are not working directly with the waste, but are essential in order to maintain the material flows and the profitability of the product. To study them properly, it will become necessary to explore the different concepts of the recycling strategies, seeing which are involved in each of them.

2. Considerations regarding different steps of the business model

To address all the possible perspectives, different concerns should be explained first. The main goal of this section is the presentation of the different assumptions or concerns used in the business model.

2.1 Collection strategy

The collection schemes studied are the real ones that are implemented in different technologies as Waste of Electrical and Electronic Equipment (WEEE), Photovoltaic (PV) panels and even aeroplanes.

- **Small scale equipment** is easy to collect if the end-user follows the established path. Assuming that a FCH technology will be for a small scale application as portable applications, there are two possibilities; the end-user calls a collection service or the end-user transport the equipment to a collection point. In the second one, the municipalities are a good option, either by creating specific collection points for the technologies or even by introducing these new technologies in the current collection services, thereby reducing the costs.

- For the **medium scale equipment**, and as far as the equipment will need for some specific operation to transport it from the end-user facilities to the collection point, the manufacturer shall provide a service with a telephone number that the end-user could contact to remove the old equipment and promote the collection. This service will be provided at the time of purchase and a way to ensure that the customer uses the service is needed. The proposal for the HyTechCycling project regarding this topic is that the collection will be done by a company whose revenues come from the producer or from the Producer Responsibility Organisation (PRO).

- Industrial or **large scale equipment**. Being true that the collection will be possible in some occasion since the devices are usually inside a container, it may be interesting to follow an in-situ recovery and dismantling process, as far as it will use the same structure for the recovery that some companies use for aeroplanes. By moving the employees and the machinery from the recycling centre to the facility, disassembly and shredding the biggest components until the equipment has been reduced to a reasonable size to be transported to separation and recycling centres. This strategy, which is used in aeroplanes, seems expensive but several recycling centres use it.

The most important one from the perspective of this business model is the medium scale, as far as it could be also valid for the large scale equipment, and due to this assumption, HyTechCycling proposal focuses on this collection strategy.

2.2 Transport of the waste

Along the whole EoL chain, there are several transport movements of the product. All these movements should be considered in the proper EoL, as far as they should be covered.

Two “base vehicles” have been selected for this study, a vehicle with a maximum load of 25000 kilograms, and another smaller which has a maximum load of 9500 kilograms. In order to estimate the costs related to transport, the average cost among both vehicles has been selected per kilometre and kilogram. [6]

Another constraint is the waste status. Nevertheless, there are no current problems raised as far as the waste has legal structures to transport even in the case of hazardous substances.

2.3 Logistics

There are several locations that are identified and who are involved in different paths. As a function of the general strategy for the EoL, some of them appear and some of them do not. These locations are the following ones:

- Manufacturer facilities
- Distributor facilities
- End-user facilities
- Intermediate storage (if applies)[3]
- Recovery centre facilities (if applies, sometimes it could be the same that the recycling centre or act as storage also)
- Recycling centre facilities
- Recycled raw materials manufacturer facilities (if applies)
- Landfill

Different paths have been finally selected to fall under the study. There have been also considered additional paths that are based on the assumption that the FCH manufacturer is also the raw components manufacturer and also this configuration has been studied. The optimal logistics will be explained in a more detailed way in each EoL scenario.

Waste logistics must take into account the location of collection points. There are WEEEs recycling centres in all the countries of Europe, so the national perspective is interesting. Moreover, the European perspective is also important. Due to it, the distances among the different locations have been identified in accordance with recycling centres, to estimate both perspectives.

Intermediate storage will appear looking for the optimisation of the transports. The idea of these storages is to save materials in order to use the transports with the maximum load, until the moment that this transport is full. In order to estimate the costs for these spaces, it has been supposed a 10000 square meters place whose cost has been broken equally for 50 years [7].

Additionally, no account has been taken of the distance towards specific purpose recycling centres, as it could be the case of Platinum Group Metals (PGM) recycling centres, as the logistic from this point of view will be based on an agreement between the general purpose and the specific purpose recycling centres, and the transport costs related to this waste flux is introduced inside the recycling costs of the general purpose centre.

2.4 Recovery and recycling process definition

The two last steps in the EoL for any type of equipment are the recovery of the valid parts of the equipment and the recycling of the non-recoverable parts. Information gathered in this project [8] shows also that the manufacturer should consider all these stages in the designing phase, as far as the recovery and the recycling process will be affected by the design in its internal process.

[3] Intermediate storage has been introduced in the computation model, which is been explained in the ANNEX I. Computational model. Nevertheless, the results show that the introduction of this location will cause an increase of the general costs of the transport and the logistic, being avoided thus in the final strategies followed.

The recovery process can be performed during the periodical maintenance inspections that the maintenance team of the producer may realise during the whole life of the equipment. Material recovery is sometimes not an option, as far as the expected useful life of the technologies is usually long, and the conditions, as it could be in high-temperature equipment could not favour this reintroduction. Additionally, the new generation of the equipment may not accept the old components [9].

All the materials that are not recoverable will be directed to recycling. The recycling process, independently of the size, will maintain the same process frame. Firstly, the FCH technology will be disassembled by manual separation of the different components. After this episode, and 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 scrap.

All these pieces will be sorted by means of magnetic separation, optical separation and more processes. More information about the process could be found in the previous work of this project[5], [9] If the equipment follows the industrial scale and the in-situ shredding, the material arrives at the recycling centre just in this stage to be introduced with the rest of the materials. Nevertheless, the core process will be the same.

After this stage, the last part of the recycling strategy should be moved the scrapped materials to hydrometallurgical, pyro-hydrometallurgical or another more specific process that allows obtaining raw recycled materials that should go to the manufacturers always ensuring the quality and the properties of the product.

The PGM will be separated from the other materials and store until the recycling centre has material enough to send the equipment to the specific recycling centres for these materials that are located in Europe. [8] Recycled ceramic materials are used in less exigent applications as in concrete manufacturing [5].

The necessary infrastructure for any recycling centre is expensive and due to it, what the HyTechCycling business model purposes is the fact that the FCH technologies recycling market should be introduced in the already existing recycling centres. Existing recycling centres are able to introduce the amount of equipment that will be recycled in the short to medium term without the need for new tools or additional space. Moreover, the operators and the logistics will be easily adapted and the initial costs of this business model are minimized.

Finally, and even if this is the worst scenario case, the landfill should also be considered as far as it will become needed if the material cannot be recycled.

The recycling target is the measure that has been used to dismiss the landfill impact. This recycling target represents over the total FCH technologies placed in the market, the amount of them that should be recycled in order to achieve the legal targets. This target could be an indicator also that measures the activities put in place to create and to maintain the EoL strategies.

A minimum recycling target of the 65 % should be completely recycled annually for all the technologies, with the exception of the PEMFC, as far as it is expected that most of this equipment came from FCEV, whose falls under the EoL of Vehicles (ELV) Directive [10]. Due to it, the PEMFC recycling target has been set higher (85 %).

2.5 Cost coverage

Using as a basis the cost optimization principle, the main goal is to reduce the monetary flows as much as possible while the recycling target per technology is maintained. To address the goal, a definition of the costs is needed.

- **Transport costs**
- **Recycling costs**: Recycling costs are the operational costs of the recycling activity. These costs are directly related to the volume that the recycling centre absorbs and also with the electricity cost, as far as the amount of electricity needed for these processes is high.
- **Secondary raw materials benefit**: The recycling centre is producing raw materials for other industries. Through the sale of these materials, the recycling centre obtains revenues. It has to be considered that the secondary raw materials will go to a market where they fit in terms of quality and price, so there may be a devaluation of profit if the market in which secondary raw materials end up is based on general purpose low-demand materials.
- **Residual costs**: These costs aim to represent the money that is leaked in the EoL strategy. Energetic valorisation costs, possible landfill or leakage of the materials out the EoL strategy will affect negatively to this business model. To estimate this value, the costs of landfill have been used from the bibliography. [11]
- **Structural costs**: The more developed the structure, the higher the costs. Because of this, once a third company enter in the structure to act and manage the collection and recycling, some costs would need to be introduced in the business model, in order to maintain the structure. This structure costs are basically the employee's salary and the spaces rents or purchase for the possible intermediate warehouses or storages.

All these costs should be covered by the actor that produces the waste stream. In all the cases, the monetary flows could be managed directly by direct agreements among the different actors. Nevertheless, as the system will become more complex, with more companies entering in the market and higher waste volumes, it will become interesting to apply the Extended Producer Responsibility (EPR) scheme with a Producer Responsibility Organisation (PRO), to centralise and improve the management.

2.5.1 EPR structure and scope

By definition, EPR "is a policy approach under which producers are given a significant responsibility (either financial or physical) for the treatment or disposal of post-consumer products." [12]. What means that is the producer or even the end-user the responsible for the waste generated even at the EoL of the product. EPR aims to promote the integration of environmental costs and management associated with goods through their lifecycles.

In the European Union, the EPR is compulsory by law in specific products as WEEEs, batteries, and vehicles[10], [13], [14]. Nevertheless, FCH technologies are not fully covered by the current legislation [15]. This cause that the scope of the EPR presented should be born from a voluntary approach, based on the potential benefits.

EPR systems have two main objectives as the Organisation for Economic Co-operation and Development (OECD) has explained [12]:

- Shift responsibility upstream to the producer and away from the municipalities.
- Incentivise producers to incorporate environmental considerations in the design of their products.

The main consequences that could motivate the creation of an EPR are [12]:.

- Manufacturers have not incentives enough to improve or redesign their product and packaging.
- Recycling targets are not achieved by any other strategy.
- The costs of the materials increase and the trend follow that path. Then, recycling is seen as a way to obtain a reduction in the costs of raw materials[4].

Manufacturers, producers and distributors, who are indeed the polluters by the definition of the law, are allowed to perform the EPR by themselves, covering the collection, the recycling and the EoL inside their own company. Moreover, if the manufacturer arranges an agreement with the recycling centre, it is still managing the waste under its own property.

However, and even the fact that the management by themselves is an option from the short to medium term, in a market with high penetration and revenues, it could be interesting the introduction of a third party company, which manage the activities related to the EoL.

PRO are the bodies that focus mainly on the collection, logistics and monetary flows of the products. The PRO could be born from a voluntary approach or from a mandatory one. Based on a voluntary approach, as far as EPR is not mandatory currently for FCH technologies, the creation could go in line with eco-objectives and costs reduction. Products such as the PV panels which have long lifecycles and has also positive waste flows has its PRO.

The HyTechCycling proposal is to emulate the system that currently is used in the PV panels and create a European PRO scheme with national divisions in the mid to long future. This European PRO will be responsible for the maintenance of the agreements if applied among recycling centres and manufacturers, while it is ensured that the recycling ratio is increased annually or at least maintained.

In order to estimate which are the maintenance costs of this European PRO, what could be assumed is an organisational structure as it is presented in Figure 4.

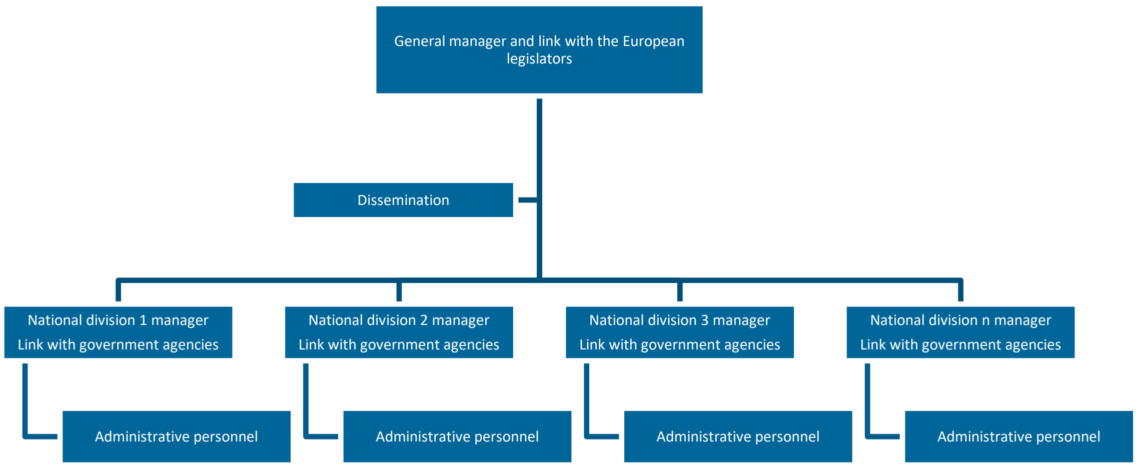


Figure 4. Purposed PRO structure distribution.

[4] This consequence has been raised from industrial actors and PROs already contacted during the development of the project.

2.5.2 Key actors involved in the EPR scheme

The EPR structure that is purposed is presented in Figure 5. In this case, it has been chosen a single PRO strategy instead of a multiple one, as far firstly it will become needed to prove that the model works before the introduction of possible competitors.

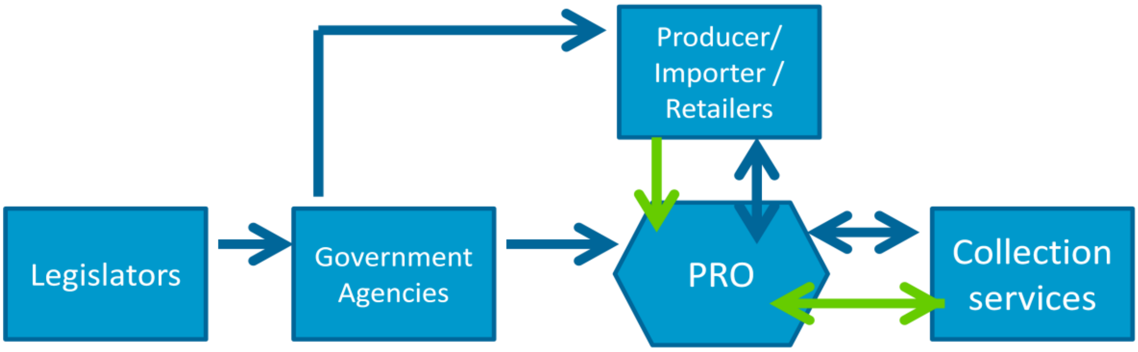


Figure 5. EPR scheme. Source: [12]

Figure 5 presents which are the relationships in the selected EPR structure. In blue colour, there are the legal links, in green the monetary flows. In a more detailed way:

- **Government agencies**: Acts as a controller or regulator of the system. In order to do so, they register the producers of the FCH technologies and also accredit the PRO. Without the registration and the accreditation, nor producers neither PRO are allowed to be involved in this EPR structure. The data collection will be done annually by electronic compulsory surveys to be submitted by the PRO to the government agencies. Thus, it is possible to check and control the data and the recycling processes in order to accomplish the targets.
- **Producers**: The manufacturers or distributors of the FCH in the EPR scheme working zone. Under the EPR scheme, they need to have legal agreements with the PRO. After that, the relationship between these two actors is based on a fee payment from the producer to the PRO in order to cover the expenses for the collection and recycling services needed.
- **PRO**: The PRO is the central actor of the EPR scheme and is responsible for making the whole system works. They present the FCH costs and, in order to make the recycling of the whole FCH technology profitable the PRO pays for them. These costs will be covered by the fees collected from the producers.
- **Commercial Collection and Processing Services**: They are specific companies that work for the logistics of the collection and the recycling centre.
- **Legislators**: They are related to the government agencies by the data collection. Legislators are responsible for defining the scope of the EPR.

3. EoL structures studied

Two different EoL structures are presented in this document that not only will look for the same objective, but also should be understood as an evolution from the simplest to the more complex one.

The evolution from one to another will be based on the costs reduction or even in the fact that the company will be more focused only in the manufacturing, leaving the recycling and recovery for other companies. The EoL structures are:

- The manufacturer-recover
- Agreements between the manufacturer and the recycling centre to recover and recycle.

3.1 Manufacturer-Recoverer. Do It For Themselves (DIFT)

During the beginning of the market introduction, the volume is small, and also the revenues. The proposal is that the same manufacturer of the FCH technology will be the actor responsible for the recovery.

In this first stage, the manufacturer should be able to collect its equipment at the EoL from the end-users. How to track the equipment is a high importance topic. The manufacturer should provide a maintenance service which allows him not only to enlarge the expected useful life of the equipment but also to control the status and track the equipment.

Once the equipment reaches its EoL, the manufacturer could collect it, and once it has arrived at its facilities, it is disassembled and checked. If the individual components such as the structure, blowers or compressors meet the requisites to be reintroduced into new equipment, this reuse will reduce the production costs.

This checking and reviewing process done in the manufacturers' facilities incurs in personnel costs. In order to introduce these costs, it has been studied the time that it is needed for disassembly the BoP and the stack. This information provided by manufacturers has been used and the cost per operator per hour has been estimated using the average salary per country, and the labour hours per country.[16]

If the individual component is not able to be reintroduced into FCH equipment the manufacturer should recycle it. In order to do so, the optimal option for the EoL is the storage of the scrapped parts until the moment when the transport for the waste is profitable, in order to send it to a recycling centre.

This specific business model has importance could be more profitable in the case that the end-user is interested in buying new equipment of the same company, reinforcing thanks to this maintenance service and tracking the image of the company and its products.

3.1.1 Key actors and roles

The manufacturer is responsible to track its equipment and to ensure the collection, as far as benefits could be reintroduced in its supply chain.

This business model could be reinforced from the producer's perspective thanks to the technical and maintenance service of the equipment. Thanks to it, the producer will be able to detect and to control its equipment while covering its technology and maintain the flow of fault information to improve the product.

Additionally, the recycling centre is only affected by the introduction of new components in its materials chain. The most common ones will be easily introduced in the common processes, while in other cases as happens with the PGM materials, a common recycling centre will storage this material till the moment will become profitable sell it to specific recycling centres.

3.1.2 Logistics

For this particular case, the logistics are based on Figure 6. By means of the manufacturer's collection service, the waste returns to their facilities and there, specific operators should disassemble it, check which components cannot be reintroduced into the product and, once there is enough material to fulfil a truck, sent all the waste to a recycling centre.

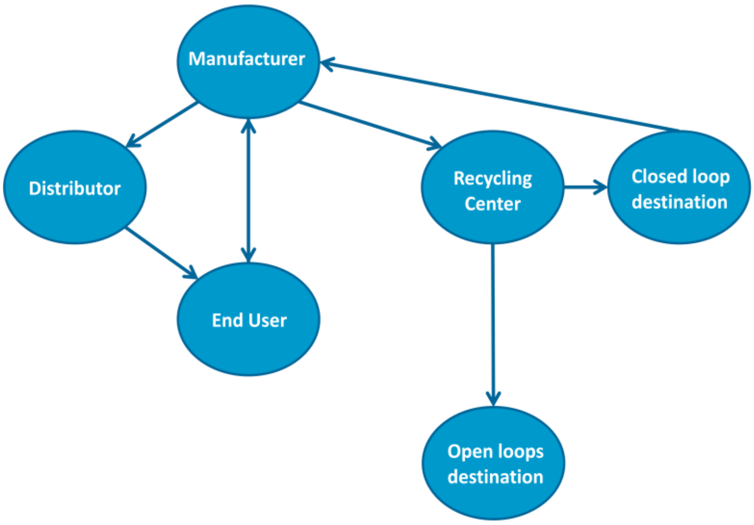


Figure 6. Short Term scenarios logistic.

3.2 Manufacturer and recycling centre agreements for the recovery.

Based on the different scenarios, the high volume of products that are predicted will cause that the manufacturers will become more focused on the production stage and decided to move the recovery and the recycling processes to the recycling centres facilities.

To achieve proper recycling targets while it is ensured that the company maintains its industrial advantages linked with the product itself, as it could be the design or the materials, agreements should be done between the manufacturer and the recycling centres.

As in the DIFT case, the maintenance service is a key point in order to control the flows of the components and the waste. Nevertheless, the collection here should be performed by a third company as far as the market is higher and the volume of waste produced should be transformed and collected in an optimal way.

The disassembly phase here will be performed in a faster way, as far as the recycling centre will look only for the most important and valuable parts, leaving the separation for the mechanical and magnetic processes.

3.2.1 Key actors and value proposition

The key actors are the producer (understanding it as manufacturer, distributor or integrator of the FCH technology), and the recycling centre.

- **Producer:** This actor should be understood as the manufacturer, the distributor or the integrator. As the polluter pays principle says the producer is the legal responsibly of the waste that it will be produced in the EoL. In order to accomplish its responsibility above the product, the producer could recycle the FCH equipment by itself or could agree with a particular recycling centre the recycling. The collection and the transport will be also covered in this situation by the manufacturer.
- **Recycling centre:** The role of the recycling centre is to recover the biggest amount of materials with optimum recovery and recycling rates. In order to work with a production company, both have to arrange an agreement. The monetary flux could go in both directions, but this will be explained in the cost coverage section. An important part of the work will be to separate and recover the components that may have a secondary use without the recycling.

Added to it, the manufacturers or the capacity to manufacture components from recycled materials is important, but not determinant. The end-users importance of this strategy is explained in section 4.

3.2.2 Logistics

After study different situation that goes among all the possibilities for the reverse logistics scheme, the optimal one from the economic perspective is presented in Figure 7 where the end waste must go directly from the end-user to the recycling centre.

This difference with the DIFT scenario decreases the kilograms moved in the basic strategies and is also valid for the recovery as far as the recovered components could go from the recycling centre to the manufacturer.

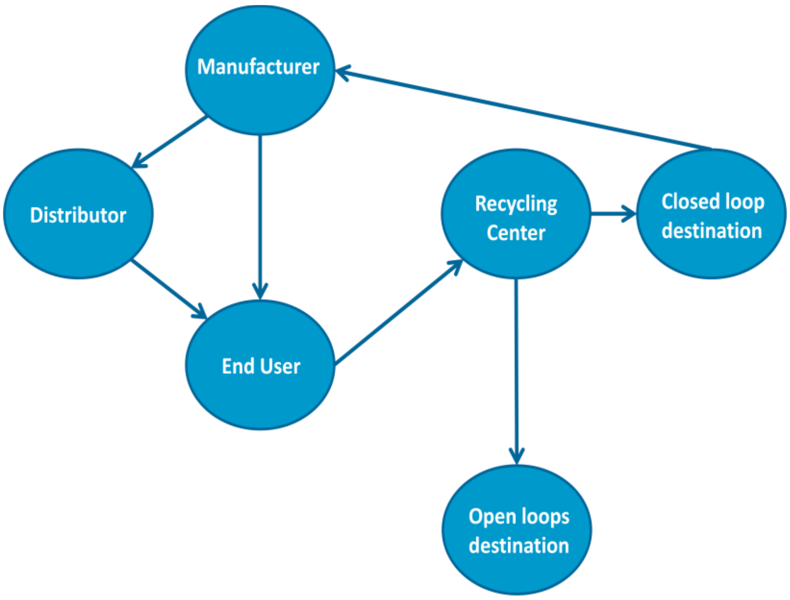


Figure 7. Long Term Scenarios

4. The role of end-users

End-users are the link between the life and use of the FCH technologies and the starts of the EoL. If end-users are not aware of the constraints and the importance of the recycling processes, the recycling chain may not start and the FCH technology will be landfilled. This is why end-users are considered a key part of the whole process in all the different strategies.

From surveys [8], and considering that the end-users are nowadays facilities or industrial customers, what means that the scale of the equipment is high (micro-CHP for residential scale is not widely deployed yet) 67% of end-users interviewed have starting to analyze EoL of the products, but they consider essential to analyze the extent to which system useful life is profitable, which will affect the time delay for the recycling strategy began as it has been presented in this document.

Today there are stacks with more than 40000 hours of operation, and the technology is constantly evolving, what causes on the one hand that the end-users are able to obtain the maximum benefit of the technology. These evolutions have been introduced in the business model with information raised from manufacturers.

The end-users are mostly able to participate in the recycling strategy by means of agreements with the manufacturer [8]. This situation currently seems to be productive, as far as the market is not excessive and the manufacturers are able to manage their equipment at the same time that they are able to protect their technology.

From the manufacturer perspective and philosophy, the end-user should not be worried about how the recycling strategy is created and works. Under its perspective, the end-user should pay a fee for the maintenance and the management of the EoL. [8]

In order to engage the end-users, information needs to be clear and efficient. Information about what happens if a fuel cell is not properly recycled, about the materials and constraints FCH equipment have are needed to be provided. Awareness is a key point to start the reverse logistics supply chain.

Moreover, the end-user will participate in the recycling supply chain if they understand its role clearly and if this participation is not time and effort consuming. When the end-user participates actively, their needs and concerns appear in the planning in a more detailed way.

Once the end-user is aware of the importance, and the technology needs to be recycled, the communication raises as a major issue to consider. How to communicate with the responsible for recycling, and how to transport technology are just two questions that will need to be solved. To do so, the FCH technology producer[5] should provide at the purchasing moment a contact which will be the link between the end-user and the producer, to manage the EoL. This contact could be the same one that works for the maintenance.

[5] Producer here should be understood as the manufacturer, integrator or distributor of the technology. Producer definition falls under the scope of the waste responsibility.

5. Waste status of a recycled raw material

An important topic in the EoL, and which will not be fully covered in this business model is the end of waste criteria. After a recycling process, the status of the recycled material could be waste or no waste. The classification as no waste is based on the fact that the recycled material complied with certain legal conditions, which are, from the Waste Framework Directive[17]:

- The substance or object is commonly used for specific purposes;
- There is an existing market or demand for the substance or object;
- The use is lawful (substance or object fulfils the technical requirements for the specific purposes and meets the existing legislation and standards applicable to products);
- The use will not lead to overall adverse environmental or human health impacts.

These criteria, which are defined by the Joint Research Centre have been applied for some components as aluminium scrap [18]–[20], but the status of the waste for some materials components should be defined in the future, as far as the status of the material will facilitate the market reintroduction, while the quality is ensured.

6. How to commit public authorities?

Public authorities have an important role in the development of a strategy for waste management of FCH technologies. They should define a legal regime that supports the correct management of waste by defining the bases and objectives for the treatment of FCH waste.

This definition should ensure that FCH waste generated is delivered and adequately managed. Possible options to be examined include deposit schemes, EPR schemes and recycling targets. A proposal for the Commission is to examine a range of measures to minimize FCH waste generation. Finally, it will continue its work to improve understanding and measurement this technology in a way to support effective prevention and recovery measures.

Innovation is a key enabler for the transformation of the FCH value chain: it can help to reduce the costs of existing solutions, to provide new ones and to boost potential benefits beyond Europe's borders. While the EU can play an enabling role, European businesses need to invest in the future and affirm their leadership in the materials value chain. Innovative solutions for advanced sorting, chemical recycling and improved polymer design may have a powerful effect. For instance, scaling up new technological solutions such as digital watermarking could allow much better sorting and traceability of materials, with few retrofitting costs.

Research and innovation will make a difference in preventing FCH pollution. The Commission should be particularly attentive to innovation on materials that are harmless for the environment and ecosystems. New approaches - developing innovative business models, reverse logistics schemes or designing for sustainability, for instance - may minimize FCH waste at source, while achieving further economic, environmental and social benefits. Finally, further scientific research is needed to gauge the potential health impacts of FCH waste and develop better monitoring tools.

But in this strategy, not only can state, regional and local authorities play an active role. Even if there is a perfectly defined legal regime at the community level, this regime should be transposed into the national and even regional system properly. Boosting the recycling activity by means of an evaluation of the legal and administrative barriers and its solution, and coordinated work with the authorities to avoid other possible concerns must be promoted to set a proper atmosphere for the recycling activities towards Europe.

7. Objectives and Key Performance Indicators (KPIs)

The objective of this task is to develop a business model which has the capacity to adapt to all the different markets that will be possible in the future for the FCH technologies. According to it, the target should be the maximization of the FCH technologies proper recycling, avoiding as much as possible the landfill at the same time that a structure with reasonable costs is created.

In order to analyse each year the success or the failures of the project, some KPIs are presented below. The amount of indicators has been selected as 7, as far as it is a reasonable number [21] to control and at the same time, provide enough information about the status of the recycling strategy.

Id	Description	Unit
KPI 1	Kilograms of FCH equipment introduced into the market	Kg/year
KPI 2	Kilograms of waste collected by the different collection services	Kg/year
KPI 3	Kilograms of waste recycled by the recycling centres	Kg/year
KPI 4	Total cost of the waste logistics	€/kilogram
KPI 5	Total costs of the dissemination strategy	€/year
KPI 6	Number of companies directly involved in the EoL	Number
KPI 7	Recycling target achieved by the recycling strategy	%

Table 1. KPIs selected for the business model

KPI 1 to 3 measures the amount of material that are annually set in the market and recycled. With this information, it is possible to estimate how to cover the different costs of the EoL of the technologies. KPI 4 gives information related to logistics.

KPI 5 presents the awareness actions performed by the actors involved, as far as not only the producer should promote the information to the customers. KPI 6 presents the number of companies that currently are involved the EoL and KPI 7 pretends to study the achievement grade of the recycling target that has been imposed (proper or impose by law) and the real recycling results.

All these KPIs are valid also for the PRO system, as far as the difference is based on the amount of information managed. Nevertheless, the PRO must do it in order to track and to declare the targets to the government bodies, so it will not incur into additional costs.

8. PESTLE analysis

In order to study, classify and identify the proper barriers that this business model could face in the future, a PESTLE analysis [22] has been done based on the previous work performed during the development of HyTechCycling.

8.1 Political

The political factors are based on the decisions made by the government.

Positive	Negative
• The new energy transition movements are pushing towards the novel technologies as the hydrogen, increasing thus the future market and promoting the economy of scales. • In each country, and born from the EU perspective, there will be compulsory recycling targets to achieve that will push the recycling business model. • Polluter pays principle encourages companies to introduce a whole life cycle perspective in the product.	• The market introduction is not homogeneous towards the EU, and this could imply the introduction of a European perspective first. • The status of waste and the end of this status is still unclear and needs to be clarified.

Table 2. Political analysis

8.2 Economic

The economic situation of the EU and more specifically the situation of the country will affect the development of the business model.

Positive	Negative
• The logistic costs could be optimized. • The reintroduction of recycled materials (meanwhile the quality is ensured) could be increased in the near future if technologies as SOFC or PEM technologies evolve. • The use of maintenance services to track the status of the components will create an added value in the professional profile of the technicians.	• The recycling costs are a function of the masses and the electricity prices. • The benefits raised from the recycling activities are related to the secondary raw materials market, and the quality of the secondary raw material manufactured should compete against mining raw materials.

Table 3. Economic analysis

8.3 Social

Social factors are related to the demography of the country and with their cultural aspects, as attitudes, beliefs or values of the population.

Positive	Negative
• Circular Economy is becoming more important in the EU, and it is become to get known by the customers, so introducing it in the FCH technologies may reinforce the eco-friendly vision of the market from the customer perspective.	• The components that are present in some technologies are considered as critical or with high importance. There are also hazards materials and due to both reasons, the reduction of these materials that is expected in the future may cause a divergence with the results presented in this business model. • Black market from specific components as PGM materials could be born, and this will cause a leakage in the business model.

Table 4. Social analysis

8.4 Technological

Based on technical innovation, cost decrease and the capacity of these solutions to participate in the business model efficiently.

Positive	Negative
• AWE technology is already well developed and it is not expected to change and evolve a lot. • Other technologies have a high possibility to reduce critical materials and to evolve into the market, reinforcing the need of the business model.	• Reuse has been discarded by some manufacturers interviewed; even when others have shown that this reuse could be feasible. • All manufacturers agreed with the reintroduction possibility of recycled materials but considering always that the quality of the recycled material is good enough.

Table 5. Technological analysis

8.5 Legal

The laws are able to affect or influence the business model. In order to consider the specific laws, the business model will face different Directives and its transposition towards national laws. The constraints linked with the EoL for the FCH technologies have been widely discussed in previous work of the project [15].

Added to them, it should be considered that the recycling centres will need to considere highly the restrictions that are currently applied from the BAT documents[23], among other legal considerations that are different per country. Additionally, standards as ISO 9000 or ISO 14000 should be achieved in the recycling industry.

8.6 Environmental

The geographical location of the recycling centres and topics related to the final deposition of the materials.

Positive	Negative
• Reduction of the needs of raw materials, reducing thus the emissions linked with its extraction and production. • Decrease of illegal dumping and landfilling	• Some materials fall under the open loops and have to be sent to energetic valorization or other uses. Even if this situation is not completely unfavourable, the future should promote the closed loops. • For specific materials, the recycling process may have a stronger negative environmental impact than the mining and extraction.

Table 6. Environmental analysis

9. Risks assessment

Linked with the barriers, there are also specific constraints that will be linked to the business model and the development of the actions carried. In order to obtain a deeper understanding of which will be the risks, the following decomposition structure is analyzed to look for the more diverse risks.

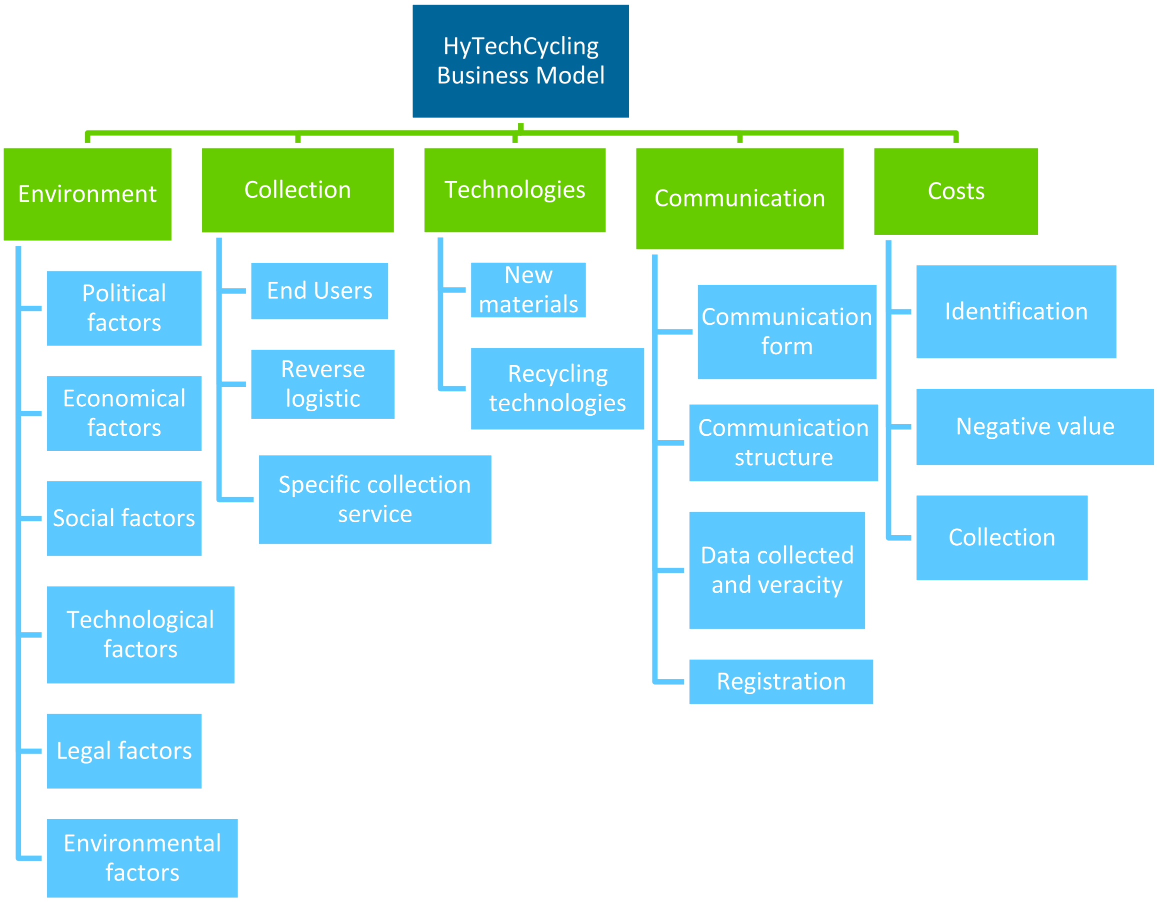


Figure 8. Decomposition structure.

As it is shown in the list presented in ANNEX II. Risk , there is a big list of different issues that could affect the business model. This list should be understood as a first approach, and each actor should study if the list fits with its vision of the business.

10. Competitors and substitutes

The HyTechCycling business model is not the only possible solution, and it has competitors and substitutes that are presented and briefly analysed in this chapter. Competitors that could face the introduction of the HyTechCycling different strategies are:

10.1 Black market of recycling materials

As the regulation No 1013/2006 defines [24], "illegal shipment" is based in moving waste out of the EU and the European Free Trade Association (EFTA) countries, and also in a shipment which does not follow the proper administrative steps as notification and consent. These illegal shipments are related to the black market of materials and recycling.

In some occasions, recycling is cheaper outside the European Union even with the transport costs consideration, and due to it, the waste movement will be done. In other cases, the shipment is related to the disposal fees [25], being cheaper or not even existing in the final destination of the illegal shipment. Another reason for these illegal shipments and recycling outside the EU is related to the environmental regulations differences between the producer country and the country where finally the waste ends.

Linked with these illegal shipments there is a black market of the materials that are recycled in places as China, India, Singapore or Ghana. The problems related to this black market are not only the ones related to the market revenues. Nevertheless, it has to be considered also that recycling in the communities is sometimes the biggest workforce and employs the biggest amount of people in the region.

The most common routes from the EU for illegal shipments and recycling are presented in bibliography [25]. To avoid the black market illegal shipments, different scope actions are needed. Firstly, the end-user must introduce the FCH technology in its EoL stage into the proper chain, avoiding thus the illegal shipments. To do so, it is possible that the end-user should pay a fee at the purchasing moment that will be returned to him at the disposal moment if this process follows the proper routes. This fee should be managed by the manufacturer or the PRO organisation.

Additionally, the regulation should become stricter and a more strict control should be performed in the borders that split the members of the Basel convention from the rest of the world, in order to control as much as possible the illegal shipments.

10.2 Raw materials suppliers that decrease the cost of their products

Here, it is needed to understand that the recycled materials that go to the market could have a positive or negative value as it has been presented in this document. However, the evolution from the positive to the negative depends on the market, and the raw materials suppliers are able to decrease their costs in order to make it more competitive.

In order to avoid problems with the raw recycling materials, the legislators are able to promote a compulsory amount of recycling raw materials in the new products that goes to the market, which will allows to the recycled raw material to be introduced in the market in a more stable and easy way.

11. Assumptions

At the recycling stage, the problem is raised by the materials that are present in the technology and not in the efficiency or the competitively of the product. Moreover, the recycling process has been set as equivalent and the structure set for all the technologies has been defined as the same one, looking from the cost coverage perspective and avoiding thus promoting differences among the FCH technologies.

As the business model aims to be valid in the future, the asbestos presented in the AWE technologies is supposed not to be present as it is banned in the EU. The specific case of AWE with asbestos should be considered separately as far as the recycling and separation of this material is extremely delicate and should be performed in a specific way.

Additionally, general results for the HyTechCycling business model have been based on some assumptions:

- The recovery ratio is small,
- The reintroduction ratio is small,
- The components that fall under the study are the stack and the BoP components (in the case of the high power electrolyser, the weight of the container has been omitted).

Finally, the volatility of the recycling costs that depends on the market is hard to model due to its relation of these costs with the electricity market and the market price of the secondary raw materials among others. Due to it, the business model has to be considered as the first approach per each technology that will need to be specifically validated in a deeper way with industrial actors.

12. Results

The study focuses in the time frame that covers from 2025 till 2050, and it also has considered the fact that the previous FCH equipment will be recycled, but its costs will be covered starting from the year 2025.

Two different scopes have been studied, one from the perspective of a single country (Spain has been selected, belonging to the tier 2 definition) and another from the complete European perspective. Both scenarios have been explained in section 1.

After studying all the different combinations, some general conclusions have been obtained as common in all the cases. A general conclusion among the different technologies is related to the transport costs. In all the situations studied, the DIFT solution has demonstrated to be more expensive in general terms and more complex to control and optimize due to the high amount of monetary fluxes. Thus, in all the strategies, the final solution has been the long term one, based on the recovery in the recycling centres by agreements. Transport costs from the agreement strategies represent around 10% of the total recycling costs meanwhile, the share in the DIFT solution is around 20%. Nevertheless, this option should be considered for new companies or small ones, as far as the benefits they can obtain are still bigger due to the recovery of the components if this philosophy is inside the company vision from the beginning.

The expected useful life evolution is presented in Figure 9. This figure is important, because as far as the expected useful life is around 15, due to the operational hours selected in this study, the recycled equipment in the year 2050 will have been sold around the year 2035.

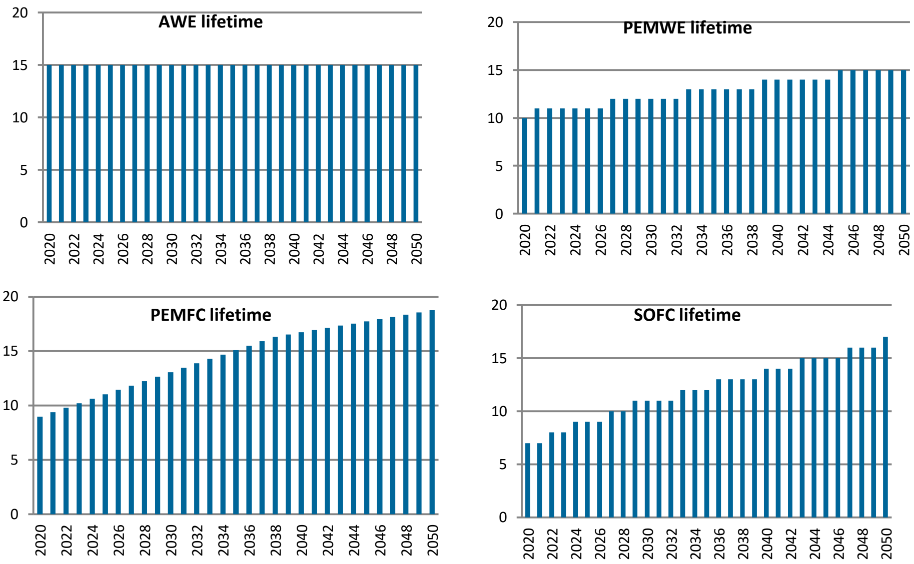


Figure 9. Lifetime evolution per technology under the operational hours considered in the business model

In a more detailed way, Figure 10 presents that the PEMFC and AWE equipment recycled in 2050 will be sold in the year 2035, when the expected useful lifetime of both technologies is 15 years. For the SOFC and the PEMWE, the equipment recycled in 2050 will be sold in 2038, when the expected useful lifetime is 12 years. Note that, the higher growth of the market is expected to happen in the year 2040. Thus, it is expected that after the period covered by this report, the market and the amount of waste to recycle will grow strongly.

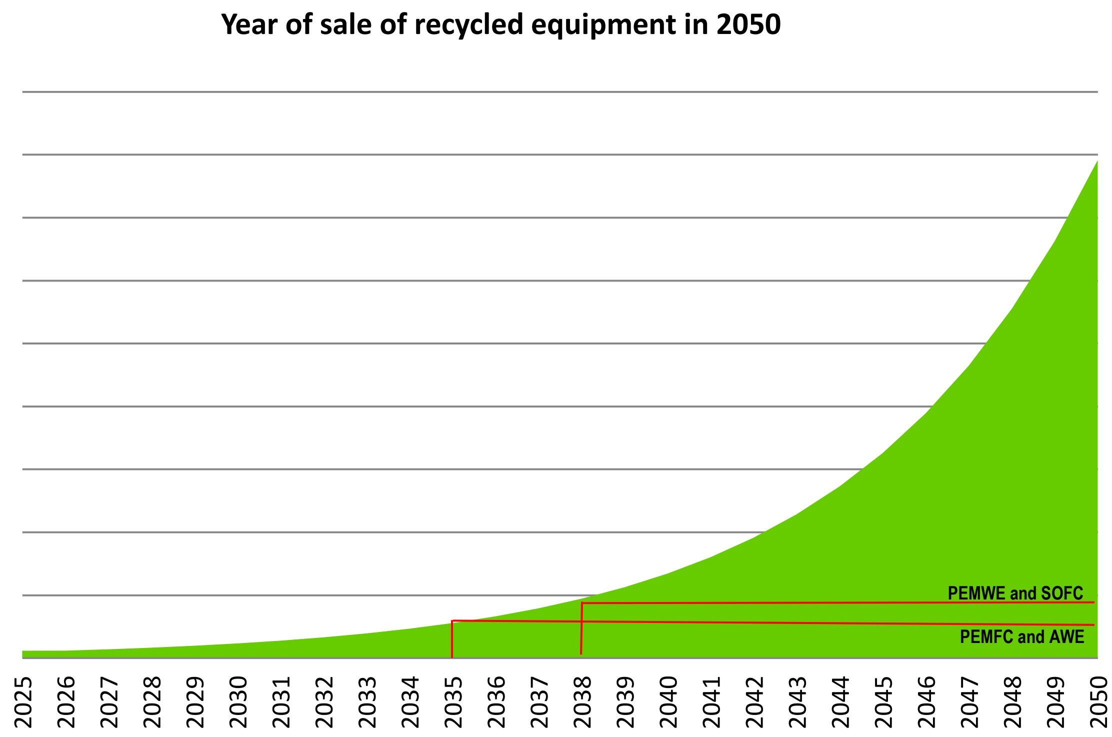


Figure 10. Year of sale of recycled equipment in 2050

Under the HyTechCycling time frame, the estimation shows that the system will assume a high amount of waste annually. Note that, till the year 2035, the technologies which have a higher expected market evolution are the AWE and the PEMFC technologies as Figure 11 presents.

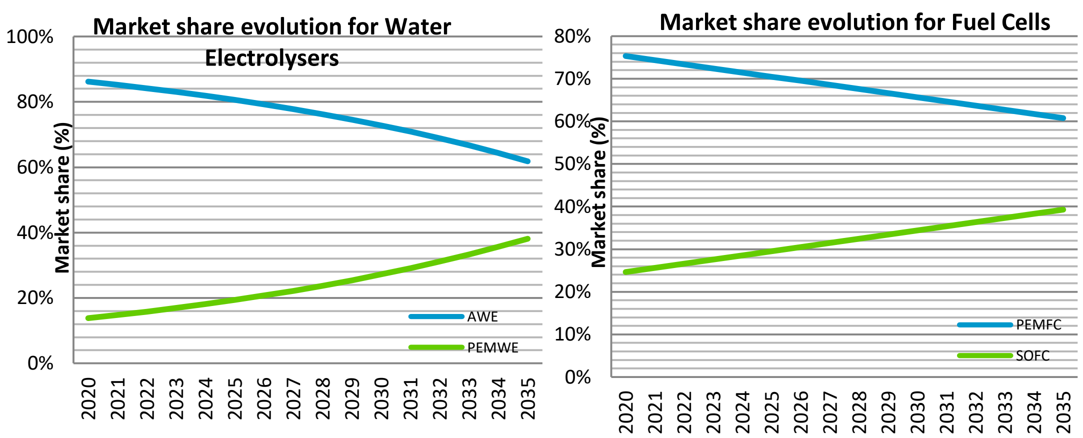


Figure 11. Market share evolution considered in the HyTechCycling project

The cumulative amounts of tonnes that are expected to be recycled by 2050 are presented in Figure 12. The differences in AWE and PEMWE technologies are based on the amount of equipment needed to cover the assumed annual power demand and the amount of equipment each scenario requires to meet that demand.

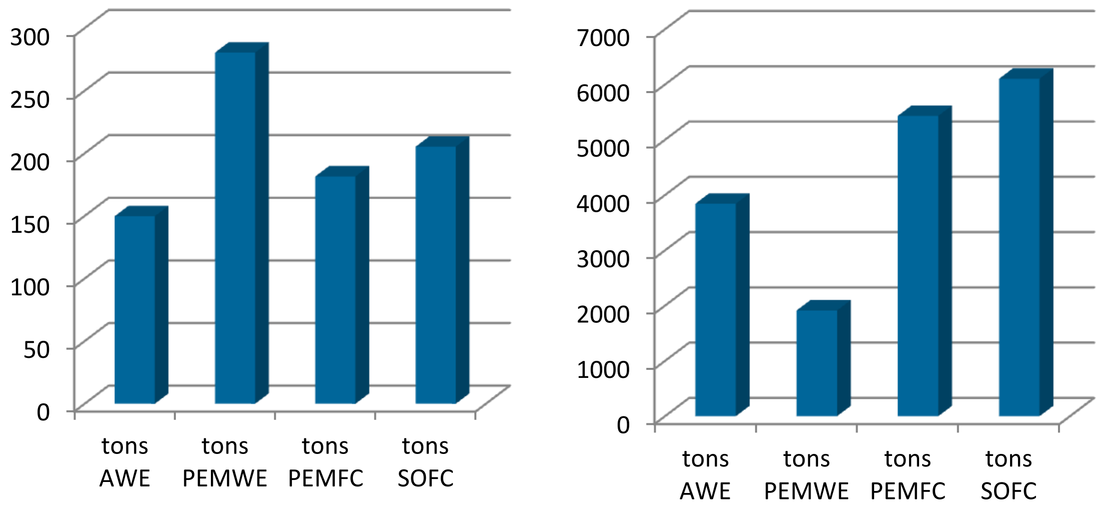


Figure 12. Expected cumulative tons of FCH technologies recycled from 2025 to 2050. National study (left) and European study (right)

The difference between the two scenarios for recycled tons of electrolysers is based on the weight of the equipment and the amount of equipment recycled. The national scenario presents more tons of PEMWE than AWE while the European scenario presents the opposite.

This is due to the demand that each scenario has to cover. The number of equipment must be sufficient to cover hydrogen demand with both technologies. The coverage ratio has been divided on the basis of the estimates presented in Figure 11. With this information, the number of equipment to recycle annually has been estimated.

The amount of material recycled by 1 PEMWE device is equivalent to the material recycled by 9 AWE under this study. Also, the power of the PEMWE equipment in this study is 6 times bigger than the power of the AWE. These assumptions mean that at a small demand and with the expected market share, PEMWE equipment will be more mass representative in the national scenario due to the slow growing of the overall market, while for a larger demand with a larger grow with the same shares, the amount of AWE equipment will grow more than the PEMWE, causing more AWE tons to recycle in general terms. The cumulative tons recycled by scenario are presented in Figure 13.

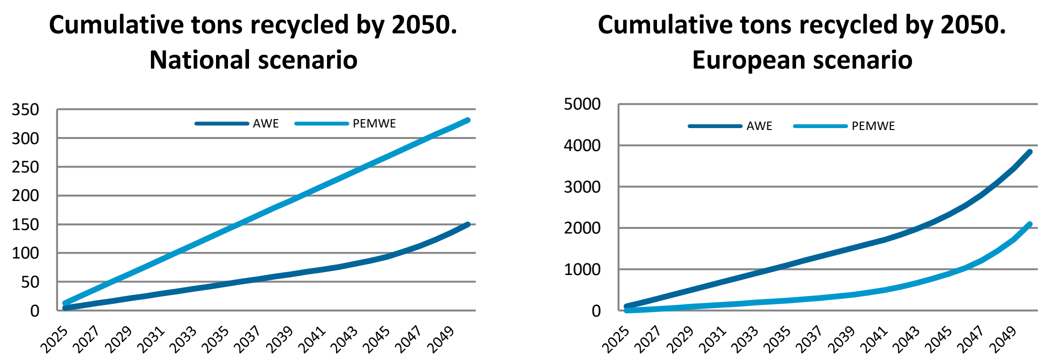


Figure 13. Cumulative tons recycled by 2050.

The rest of this section will analyse for the whole recycling chain which the costs are (assuming the operational cost of the recycling centre, the transport and also costs linked with the materials that will not follow the proper recycling path).

The benefits that a recycling centre may obtain for selling the secondary raw materials are also presented. These benefits may depend on the market and also the quality of the secondary raw material, and due to it, they may suffer from deviations linked to the market or with the improvement of the recycling processes. A general estimation based on contacts with recycling centres for the current costs has been used as a basis.

Finally, a proposal on how to cover the costs and how to boost the recycling scheme based on the costs is presented.

12.1 Costs for the recycling

As has been explained before, the costs related to the recycling as an overall are linked with the transport, the recycling centre cost and the materials that are lost or not collected (as far as this waste must be considered as landfill). Among all the costs, the most sensitive one is the operational cost for the recycling centres.

Note that the recycling centres considered in this business model are current ones. Due to it, any costs linked with re-adaptation are considered. Nevertheless, the operational costs are related to the volume and also to the electricity cost, being in most of the cases the recycling centres part of the high electricity consumption industry. Due to it, the operational cost for the recycling centre will vary annually and it is sensitive to the electricity market and its evolution.

This business model has considered the costs will be at least maintained in the future, showing the best case scenario. The best practice in order to decrease the operational costs is based then in the use of highly efficient machines and processes, optimizing then the electrical costs.

The expected costs evaluated per technology under the national and European scope are presented below, separated by technology. All the figures have two different graphs, the first one represents the national study, and the second one presents the European. Moreover, from the three different scenarios, only two of them are presented (the least and the most optimistic ones, that are presented in Figure 1).

12.1.1 AWE and PEMWE

AWE technology which is currently mature, with a stable expected useful life, will still increase its sales because in the short term it is more mature than PEMWE technology. As the Figure 14 presents, the annually recycling costs obtained from this trend evolve from 20 k€ (400 k€ in the European scenario) in 2025 to almost 60 k€ (one million and 600 thousand €) in the year 2050 for the optimistic implementation scenario. As it has been explained previously, the market at this stage will assume a small fraction of all the waste that will be treated in the future, as Figure 10 shows.

Among the different scenarios, the difference is not big enough to be appreciable until the year 2040. This is caused by the fact that the trend difference between both scenarios is similar until the year 2030 when the market is expected to explode.

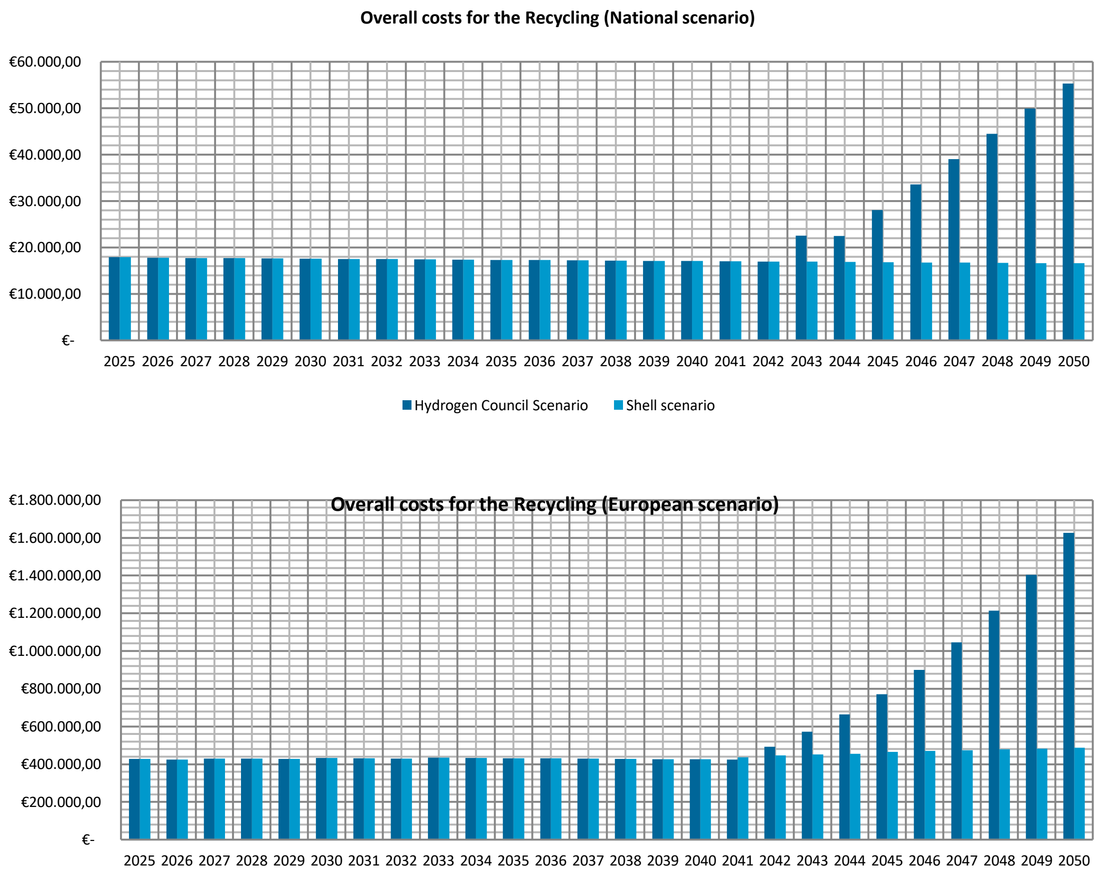
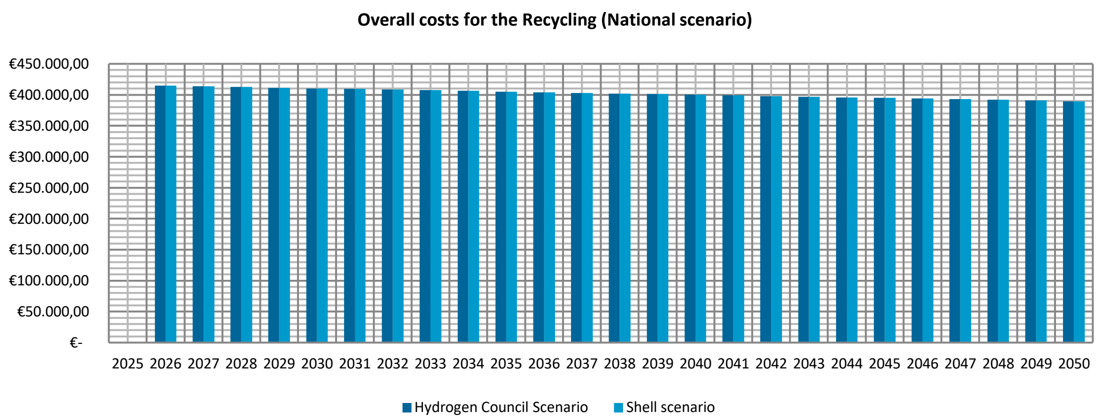


Figure 14. Overall cost for the recycling for the AWE technology.

Considering the PEMWE market evolution, the national scenario presents higher costs, but the evolution is more stable than the AWE costs. It is important to remember that the lifetime for the PEMWE is evolving from the 10 years of operation to 15, and the sales of this equipment will evolve slower than other technologies. Due to it, at the national level, the amount of equipment is more stable, and also are the recycling costs (Figure 15). On the other hand, considering the European strategy, the costs increase as the Figure 15 presents, arriving at > 11 million € for the year 2050 because the individual cost per equipment recycling is higher than the AWE.



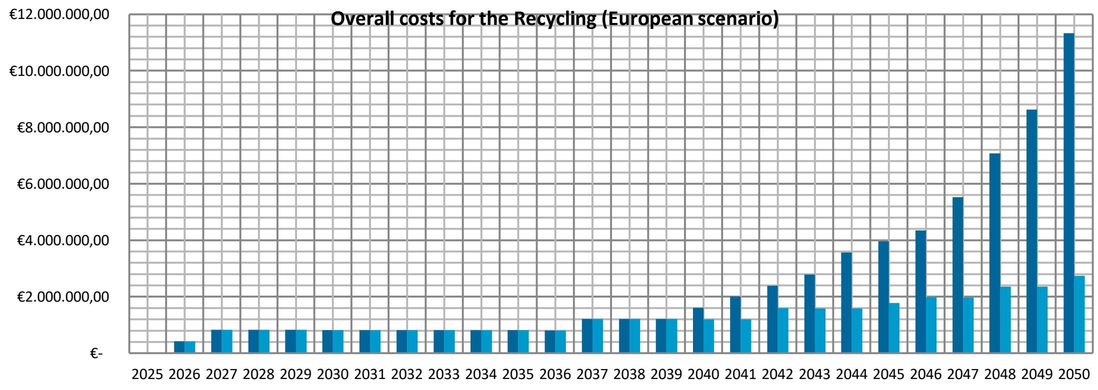


Figure 15. Overall cost for the recycling for the PEMWE technology

Considering the global costs for the recycling centres, in the most optimistic sales scenario, it will cause total costs for the recycling centres to accomplish the proper EoL of the water electrolysers technologies that evolve from half million in the year 2026 to near 12 million € in the year 2050 in the European scenario.

12.1.2 PEMFC and SOFC

Considering fuel cells, the results for the overall costs for the recycling are presented in Figure 16 and in Figure 17 for PEMFC and SOFC respectively. Summing up both cases the total costs are expected to be higher in the PEMFC recycling market, due to the higher amount of PEMFC devices.

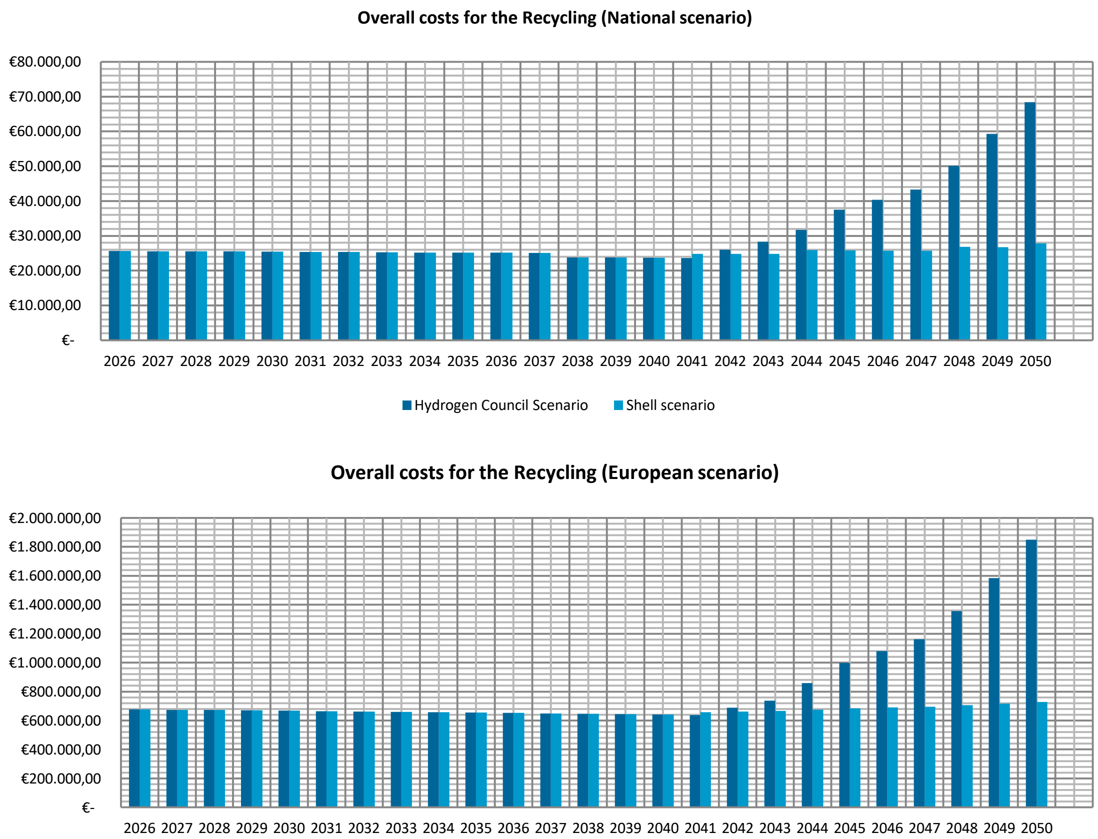
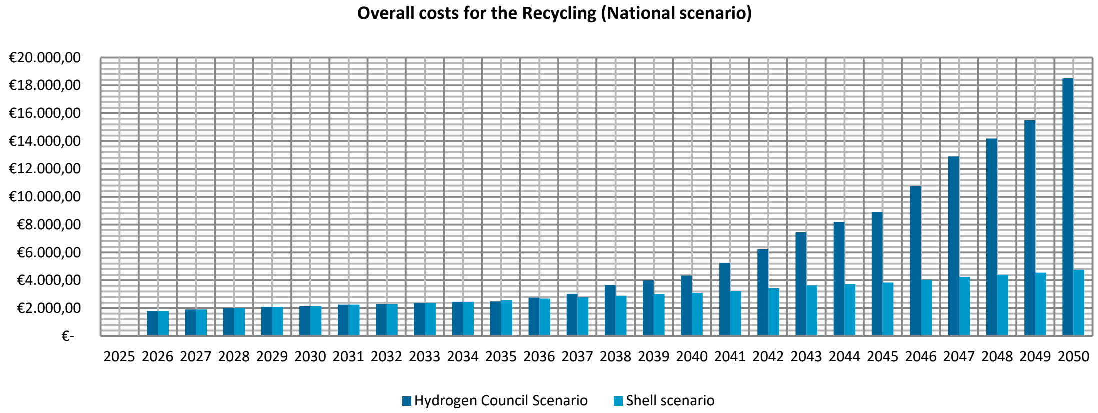


Figure 16. Overall cost for recycling for the PEMFC technology

SOFC technology presents smaller costs for recycling, which are linked with the number of common metals and ceramics that are present in this technology. The PEMFC presents higher costs related to the PGM materials and specific plastics presented in the technology. Due to it, the expected recycling costs in the future for the PEMFC may arrive at the 70 k€ (even to 2 million of € in the European scenario) meanwhile for the SOFC the costs are currently one third of PEMFC case.



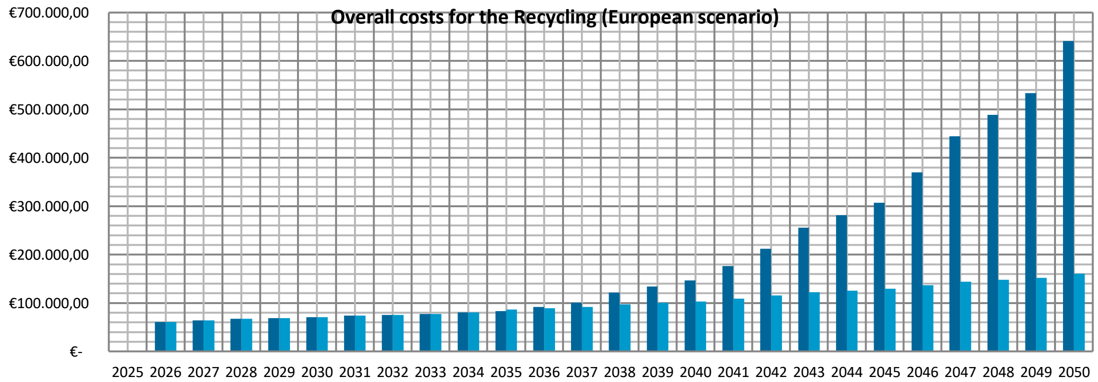


Figure 17 Overall cost for recycling for the SOFC technology

Even the high difference between all the technologies studied, the global costs for the recycling for the fuel cells will evolve from 800 k€ in the year 2026 to the 2.5 million scale in the year 2050 in the European scenario.

12.2 Benefits of selling secondary raw materials

The benefits of the recycling centre linked with the sales that they can obtain from the recycling activity are estimated in the frame of this project. To estimate the benefits, recycling centres information has been considered. One important topic has been presented previously, the recycling centres benefit will increase if their processes are able to obtain materials with high quality as secondary raw materials. Moreover, as a function of the volume that they recycle, the more material recycled, the higher are the benefits the recycling centre obtain.

The benefit of each FCH technology depends on three topics:

- The materials presented in the technology.
- The amount of each material presented in the equipment.
- The market for the secondary raw material. In this topic is where the quality of the secondary raw material is important. Currently, and using as an example ceramics, there is no current technology that allows the recycling and obtains a quality that allows closed loops for them. Due to it, the destination of these ceramics after the recycling is raw material for concrete, what causes an important decrease in the market value.

Figure 18 presents the difference between the cost per kilogram that the end-user pays for each technology and the benefit for a secondary raw material that the recycling centre obtains. As it is clear, the difference is huge.

In order to increase the benefits for the secondary raw materials, novel recycling processes more efficient are needed. Additionally, if the manufacturers reintroduce secondary raw materials that maintain the quality requirements in the new equipment, it will cause also a reduction in supply costs for them.

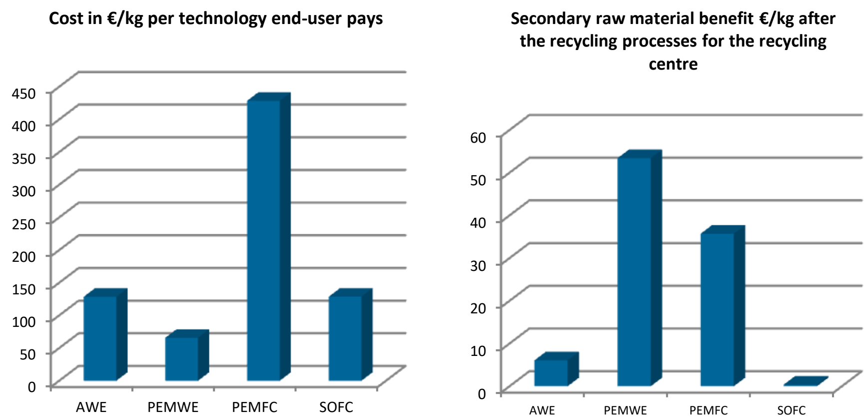


Figure 18. Comparison among cost per kilogram at the purchasing moment and after the recycling activity.

Even if the benefit per kilogram is important, the costs for recycling are also important. From the difference of both terms appears the definition of residual value, which is presented in Figure 19. This value shows that the benefits for the recycling centre with the PEM technologies is important, meanwhile for the recycling of the SOFC technology, the recycling centre activity incurs in general losses. With this value and the global values, the next section presents how to manage and cover the costs per technology.

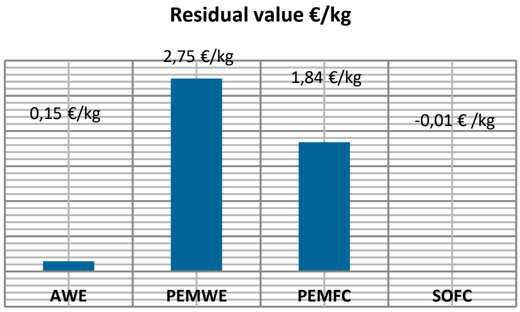


Figure 19. Residual value for the recycling centre per technology.

12.3 How to proceed

As a function of a positive or a negative residual value a proposal to cover the end of life cost is presented in this section. Note that, even if the polluter pays principle is used as a root, in some cases, recycling centres benefits allows them to cover the recycling costs without losses.

Additionally, this section will be based on the European scenario, which is the one with the highest cost and benefits, covering thus the solution of the expensive situation properly. The national scenarios may follow the same structure, but based on the European market, a general perspective is understood as more important.

12.3.1 Positive residual value

For those technologies with a positive residual value, the proposal is based on the fact that the recycling centre will cover the recycling. Based on the benefits, and also in the costs, the recycling centre will be able to cover also the transport and collection expenses while maintaining a profit in its accounts. Figure 20 shows the amount of benefit the recycling centres will maintain after the cost coverage for the PEMFC technologies considered in this business model.

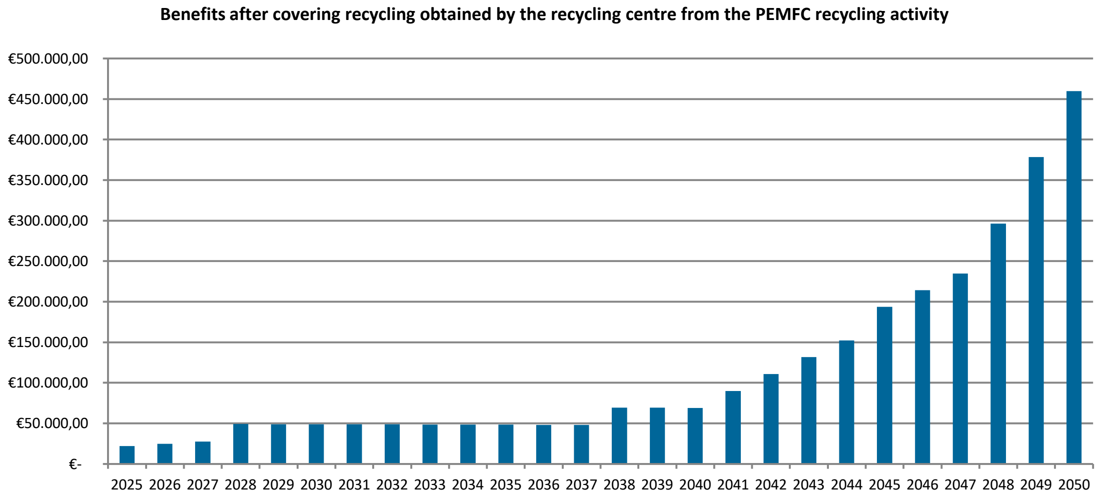


Figure 20. Benefits after covering EoL for the recycling centre

12.3.2 Negative residual value

For the SOFC technology, and as far as the residual value is negative, meaning losses for the recycling centre, the proposal is based on an increase of the €/kW price for the end user, in a small percentage of a 0.05% presented in Figure 21. With this value, the manufacturers should obtain benefits enough to cover properly the EoL of these technologies. Note that those costs are presented in blue, and as far as the market evolves and the manufacturer sales will increase, there will be more income that the amount of money needed for the annual cost coverage. This extra income (in red) may be used for novel measures, developments or even research for these technologies not only in the manufacturing stage but also in the recycling stage.

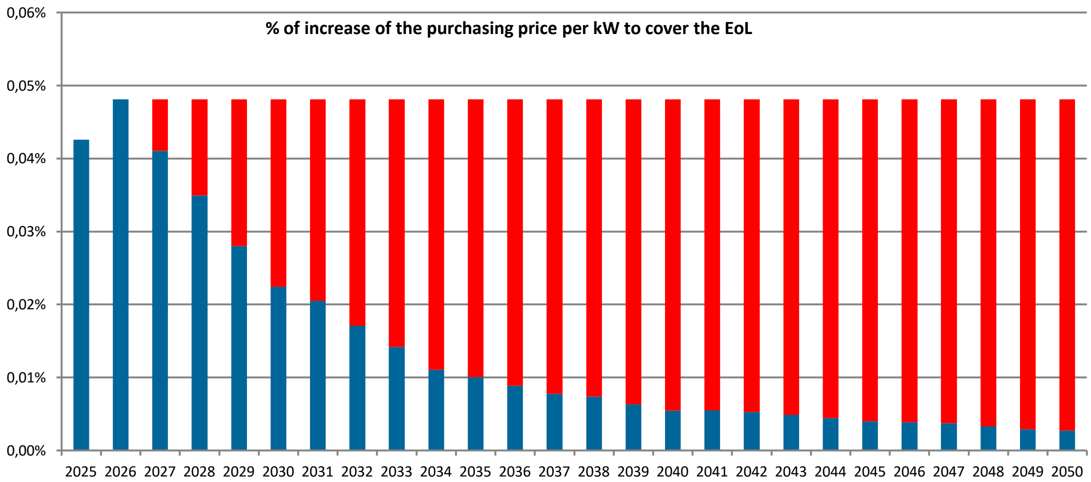


Figure 21. Percentage of increase the €/kW at the purchasing to ensure the EoL cost coverage from the manufacturer perspective.

13. New business model, rent instead of sale

Following the social evolution of the world population, the new behaviour towards sustainability is an important trend to consider in the whole business model of FCH technologies. The society tends to not purchase cars but to rent them, the companies prefer in some situation rent the equipment and pay for maintenance and a good operation services instead of the purchasing and maintenance in situ. Due to it, it could be interesting changing the philosophy that follows the linear business model that FCH technologies, among other consumer goods, has nowadays, towards a more circular scheme.

What this proposal pretends to declare is the possibility of renting the equipment by means of a renting fee. In the renting costs should be introduced the transport, the maintenance, the manufacturing and the end of life strategy of the product. In this situation, the producer will not receive all the incomes from the first moment, but it will receive it as time pass and the degradation occurs.

Moreover, and as far as the equipment returns to the producer facilities with a higher frequency than in the previous case, the producer is able to run preventive maintenance and also a corrective one if needed in order to control and to promote a more stable situation, increasing thus the life of the equipment.

14. Conclusions

The first conclusion raised from this study is based on the expected useful life. As it has been demonstrated in section 12, the recycling market in 2050 will be working with the waste that has been introduced in the market in 2035. Assuming that the market will grow as it has been assumed in section 1, the biggest increase in the recycling chain will be faced by recycling centres out of the frame time of this project.

After all the work presented in this document, the proposition that the HyTechCycling business model purposes is a function of the residual value of the recycling centre in order to minimize the costs and to achieve good results in the EoL of the technologies is the next one:

- **Positive residual value:** As far as the recycling centres will obtain profit for the recycling of both technologies (mainly related to the PGM and other valuables metals presents in both technologies), and being a fact that under the perspectives of this business model, the recycling centre will still obtain revenues for the recycling even if it covers the costs for the whole chain, the HyTechCycling proposition is that the cost coverage will be performed by the recycling centre.
- **Negative residual value:** The costs for the EoL of the SOFC technology should be managed by the manufacturer, as far as the recycling centre (at this current moment) lose incomes for the recycling activities.

The extra costs that should be managed by the manufacturer may be obtained at the purchasing moment with a slight increase in the costs of the product. This cost evolves, nevertheless, the HyTechCycling project envisages to maintain the price increase, and to dedicate these extra revenues in new recycling technologies, new research and development and more environmentally friendly solutions.

Note that novel technologies in the recycling phase will be presents also in future. The development costs of these technologies should be shared among manufacturers and recycling centres, as far as these novel technologies will help to develop the closed loops.

The recycling costs, that in all the cases are the most important actor for the monetary fluxes, depend on market variation. At the beginning moment when a company wants to start with the recycling, HyTechCycling partners suggest looking for a detailed status of the recycling values, as far as the costs may have varied since the development moment of the business model.

The introduction of a PRO seems to be reasonable from the HyTechCycling consortium in the future, as far as the total amount of revenues and monetary fluxes that are predicted has a volume high enough to make profitable the management from a PRO structure.

Even the fact that the cost coverage will be in some cases omitted for the manufacturer, this actor must in all the cases work towards the circularity of the technologies, as far as they are the creators of the equipment and the actor with more capacity to influence the future of the equipment (materials, modularity, efficiencies, etcetera...)

All the work presented in this document needs active involvement from the actors identified. Manufacturers and recycling centres will be the actors more involved, as far as its revenues and also their marketing will depend on this work. However, end-user involvement is also a key point, as far as the whole recycling chain as always the end-user as the beginning of the process.

Bibliography

[1] Convención Marco sobre el Cambio Climático, 'Acuerdo de París sobre el Cambio Climático', UNCCC, Paris, 2015.
[2] Shell International, 'Shell Scenarios Sky. Meeting the goals of the Paris Agreement', Shell International, Mar. 2018.
[3] Hydrogen Council, 'Hydrogen scaling up. A sustainable pathway for the global energy transition.', Hydrogen Council, Roadmap, Nov. 2017.
[4] Miguel Zarzuela, 'HyLaw Proyecto HyLaw y sus implicaciones en Europa. Situación normativa nacional y recomendaciones de las tecnologías del hidrógeno y las pilas de combustible', CDTI, Madrid, Spain, 18-Sep-2018.
[5] A. Valente, D. Iribarren, and J. Dufour, 'End of life of fuel cells and hydrogen products: From technologies to strategies', *International Journal of Hydrogen Energy*, Feb. 2019.
[6] Ministerio de Fomento, 'Observatorio de Costes del Transporte de Mercancías por Carretera.', p. 79, Jan. 2016.
[7] 'Naves prefabricadas precios economicos o baratas. PATEC'. [Online]. Available: https://www.patec.org/naves-prefabricadas-precios.php. [Accessed: 28-Feb-2019].
[8] Sabina Fiorot, Davide Damosso, and Federico Cartasegna, 'Report on feedback to new technologies and strategies and focus on', Deliverable 5.2.
[9] Alfonso Bernad, Ana Maria Férriz, Adolfo Gaspar, Marcelo Liendo, and Lorenzo Castrillo, 'Study on needs and challenges in the phase of recycling and dismantling', Deliverable 2.5.
[10] European Comission, *Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles*. .
[11] European Environmental Agency, 'Managing municipal solid waste - a review of achievements in 32 European countries'.
[12] OECD, *Extended Producer Responsibility: Updated Guidance for Efficient Waste Management*. OECD, 2016.
[13] European Comission, *Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators and repealing Directive 91/157/EEC*. .
[14] European Comission, *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) (recast)*. .
[15] Sabina Fiorot, Davide Damosso, and Federico Cartasegna, 'Recommendation and perspective on EU regulatory framework', Deliverable 2.4.
[16] 'El salario medio que se cobra en cada país europeo (y España no está en el top 10)', *idealista/news*. [Online]. Available: https://www.idealista.com/news/finanzas/laboral/2018/05/24/765801-el-salario-medio-que-se-cobra-en-cada-pais-europeo-y-espana-no-esta-en-el-top-10. [Accessed: 28-Feb-2019].
[17] European Comission, *Directive2008/98/EC ot the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives*. .
[18] 'Council Regulation (EU) No 333/2011 of 31 March 2011 establishing criteria determining when certain types of scrap metal cease to be waste under Directive 2008/98/EC of the European Parliament and of the Council', p. 10.
[19] 'Commission Regulation (EU) No 715/2013 of 25 July 2013 establishing criteria determining when copper scrap ceases to be waste under Directive 2008/98/EC of the European Parliament and of the Council', p. 7.
[20] 'Commission Regulation (EU) No 1179/2012 of 10 December 2012 establishing criteria determining when glass cullet ceases to be waste under Directive 2008/98/EC of the European Parliament and of the Council', p. 6.
[21] PriceWaterHouseCoopers, 'Guide to key performance indicators'. .
[22] Business Makeover, 'PESTLE'. .

[23] 'DECISIÓN DE EJECUCIÓN (UE) 2018/ 1147 DE LA COMISIÓN - de 10 de agosto de 2018 - por la que se establecen las conclusiones sobre las mejores técnicas disponibles (MTD) en el tratamiento de residuos, de conformidad con la Directiva 2010/ 75/ UE del Parlamento Europeo y del Consejo - [notificada con el número C(2018) 5070]', p. 53.
[24] *Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste*, vol. 190. 2006.
[25] D. Kellenberg, 'The Economics of the International Trade of Waste', *Annual Review of Resource Economics*, vol. 7, no. 1, pp. 109–125, Oct. 2015.
[26] Lotrič A, Stropnik R, Mori M, Drobnič B, Jurjevčič B, and Sekavčnik M, 'Assessment of critical materials and components in FCH technologies', Deliverable 2.1.

ANNEX I. Computational model

In order to estimate the cost coverage of the business model, a computational model has been created. This computational model has been developed to assess properly how the costs will evolve pretending to decrease the uncertainties.

INPUTS

The computational model uses the following inputs:

- Demand of hydrogen per scenario: This data has been adapted to the European level and also to the national one. The national level, which has been used to study national strategies in the End-of-Life, has been defined using a factor related to the market and development of the hydrogen economy in the country, using the tier definition of the HyLaw project.
- Technologies information: Each technology has been identified with a "type" model from different manufacturers. This "type" model is based on the weight of the equipment and the power.

Technology	AWE	PEMWE	PEMFC	SOFC
Weight (kg)	1400	12750	42	195
Power (kW)	90	560	12	2,51
Kg/kW ratio	15,55	22,76	3,5	77,68

Table 7. Technologies information input for the computational model.

- Expected useful life and its evolution per technology: This data is introduced to represent the limit time when the full equipment is replaced. Information about this expected useful life has been obtained in accordance with different manufacturers. The lifetime has been studied in years, and the operation hours per year have been set as 4380 hours for all the technologies instead the PEMFC. PEMFC's operational hours due to the expected use of the technology in the mobility sector has been set smaller.

Year	AWE	PEMWE	PEMFC	SOFC
2018	15	10	8	6
2025	15	11	11	9
2050	15	15	17	17

Table 8. Expected useful life estimation in years per technology.

- Market share ratio per technology: The market share per technology aims to represent how the different technologies evolve and also how the different technologies sales changes in the time. Information is presented in Figure 22.

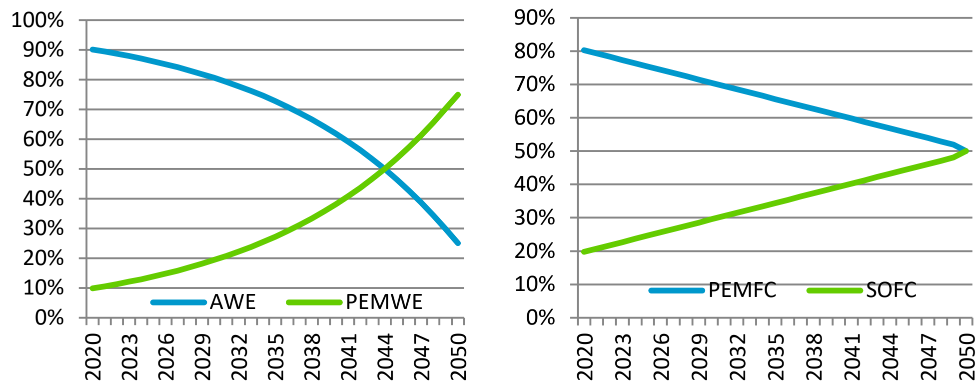


Figure 22. Market share expectations per technology. Own elaboration.

- Distances among different actors: The distances among all the actors' facilities have been introduced in accordance with data provided by recycling centres and manufacturers. This distances changes in the study if the scope is national or European.
- Percentage of kilograms that follow each path as a function of the transport strategy selected: As part of the optimization for the different transport strategy, each of them has a different amount of kilograms that follow each path. Due to it, each strategy considered all the differences.
- Costs and benefit for the recycling centre per technology: Based on the percentage in weight used in this project [26], and using the costs and benefits that recycling centres have provided, an estimation of the costs for the recycling and also the possible benefits that the recycling centre will obtain for its activity has been introduced.
- Recycling ratio: Relation among the amount of equipment that are collected and the amount of equipment that are introduced into the market.

COMPUTATION

With all the inputs introduced in the computational model, the algorithm is prepared to firstly estimate the amount of "type" equipment needed to cover the annually energy demand related to hydrogen.

All these equipment will be recycled at the end of its expected useful life at the purchasing moment, using the expected useful life evolution that has been introduced, this delay is also applied and then, the kilograms that are recycled are calculated.

The second step of the algorithm is the optimization of transport. The criterion used has been to minimize the related costs, which are based on the different paths per transport scenario, the average cost per kilometre and per kilogram and the amount of equipment collected. With this information, for the DIFT scenario, the disassembly process has been considered in the manufacturer stage meanwhile in the agreements scenario, the disassembly costs are linked with the global recycling costs.

In this transport costs, the scenarios that have considered the intermediate storage consider here also the costs related to the building, as far as till the moment that the FCH technology does not arrive at the recycling centre facilities, all the costs are summed under the transport cost definition.

Once the transport costs have been optimized, the costs related to the recycling and recovery activity are computed, based on three different ratios, the materials direct reuse ratio, the recycling ratio, and the reintroduction of the materials in the newly manufactured equipment ratio.

The recovery ratio has been established as zero as it is explained in this document, and the reintroduction ratio has been also minimized due to the need for a quality revision firstly.

Moreover, the cost related to all the equipment no recycled has been calculated considering the worst case scenario and assuming that these equipment are land filled the costs related to this landfill are estimated in order to address losses related to the end of life.

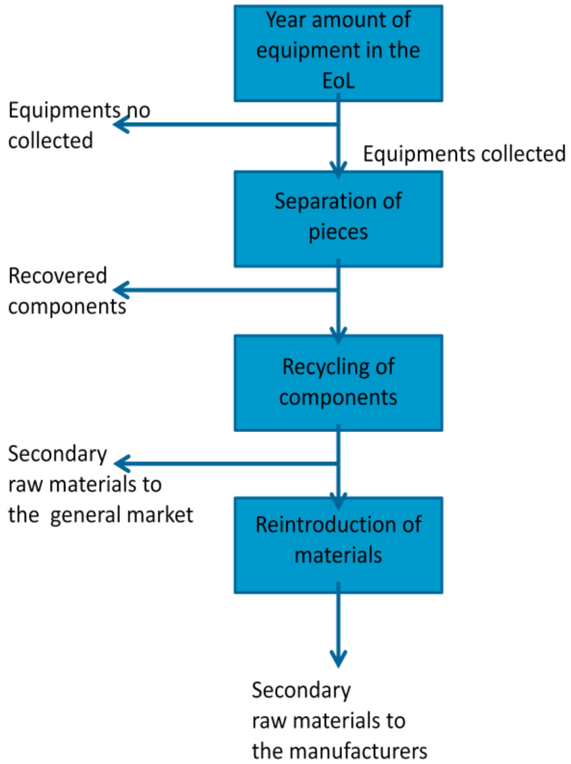


Figure 23. Mass distribution for the cost computation in the computational model.

RESULTS

The results of the computational model are compiled in an Excel file and analyze. The final results are explained in the Results section of this document.

ANNEX II. Risk assessment

Group	AREA	Risk Cause	Risk
A	Economical	There is no a huge market and the manufacturers are not interested in the EoL	Funding problems for the PRO
A	Economical	There is no a huge market and the manufacturers are not working with the EoL	Lack of interest and lack of recycling. More waste to the landfill.
A	Legal	There is no compulsory approach for the EoL	FCH technologies not recycled
A	Legal	The requirements that BREF and BAT documents purposed are not achieved in the recycling centre	Extra costs for the recycling centre for the recovery operations
A	Legal	The waste status is not clarifies properly and this situation causes difficulties in the recycling chain	
A	Political	Fuel Cell entered under the scope of batteries directive	Different recycling centres and legal considerations
A	Social	No eco-label apply to FCH technologies	Small dissemination about the importance of the recycling of the FCH technologies
A	Social	Black market of FCH technologies will avoid the PRO and produces a non proper recycling strategy	Leakage in the recycling scope of the project
A	Social	End-user not aware of the importance of the recycling	Leakage in the recycling scope of the project
A	Social	End-user are not aware of the problems related to black market	Leakage in the recycling scope of the project
A	Social	The salaries for the operators that disassembly the technology becomes extremely high	Increase in the recycling costs.
A	Technological	The manufacturer is not able to track its device	Leakage in the recycling scope of the project
A	Technological	The recycling centre does not know which are the materials related that are part of the FCH technology	Delays and extra costs on the reintroduction of the recycled raw materials into the market
A	Technological	The manufacturer does not provide information for the recycling centre	Inefficient recycling strategy/Delays and extra costs on the reintroduction of the recycled raw materials into the market

Group	AREA	Risk Cause	Risk
A	Technological	The recycling process is not able to obtain a recycled raw material with quality enough to create a closed-loop in recycling	Introduction of the material in an open-loop
A	Technological	There is no market for a second hand FCH technology	More market for the FCH technologies recycling strategy
A	Technological	The technologies growth differs from the one estimated for the business model	
A	Technological	The materials are not able to be reintroduced due to the low quality of the recycling process	
B	Collection, End-users	The end-user does not start with the proper recycling	Leakage in the recycling scope of the project
B	Collection, End-users	The end-user starts an illegal loop with illegal recycling processes	Leakage in the recycling scope of the project
B	Collection, Reverse Logistics	The costs are high for the FCH technologies	Extra costs for the recycling centre for the recovery operations
B	Collection, Reverse Logistics	The collection points are far away the recovery/recycling centre	Extra costs for the collection scheme and for the PRO
B	Collection, Specific Collection Service	The collection service for the small users does not work properly	Extra costs for the collection scheme and for the PRO
B	Collection, Specific Collection Service	The collection service for the small users is expensive	Extra costs for the collection scheme and for the PRO
B	Collection, Specific Collection Service	The time for the collection is long	Delays and extra costs on the reintroduction of the recycled raw materials into the market
C	Technologies, New materials	New materials that appears in the FCH technologies, which are able to be recycled	More market for the FCH technologies recycling strategy
C	Technologies, New materials	New materials that appears in the FCH technologies, which are not able to be recycled	Land filling of materials

Group	AREA	Risk Cause	Risk
C	Technologies, Recycling technologies	High costs for the introduction of new measures	Extra costs for the recycling centre for the recovery operations
C	Technologies, Recycling technologies	Recycling technologies not available at the industrial scale	Land filling of materials
D	Communication, Communication Form	The indicators required for the manufacturers is not useful	Cost coverage calculation distant from the reality
D	Communication, Communication Form	The indicators required for the recycling centres is not useful	Cost coverage calculation distant from the reality
D	Communication, Communication Form	The indicators required for the collection services is not useful	Cost coverage calculation distant from the reality
D	Communication, Data collected and veracity	The information does not represent the reality	Cost coverage calculation distant from the reality
D	Communication, Registration	The manufacturer does not register in the PRO, but its products enter in the PRO scope and are recycled	Extra cost for the PRO
D	Communication, Registration	The registration is time consuming and not friendly neither compulsory	Leakage in the recycling scope of the project
E	Costs, Collection	The costs for the collection of the small scale collection points are expensive	Extra costs for the collection scheme and for the PRO
E	Costs, Collection	The cost for the collection of the industrial scale are not competitive and it becomes necessary to change the strategy	Extra costs for the collection scheme and for the PRO
E	Costs, Identification	The indicators required for the manufacturers is not useful	Cost coverage calculation distant from the reality
E	Costs,	The indicators required for the recycling centres is not useful	Cost coverage calculation distant from the reality

Group	AREA	Risk Cause	Risk
	Identification		
E	Costs, Identification	The indicators required for the collection services is not useful	Cost coverage calculation distant from the reality
E	Costs, Negative Value	The amount of materials with negative value is high	Extra cost for the PRO
E	Costs, Negative Value	The materials with positive value become negatives due to competence	Cost coverage calculation distant from the reality