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TECHNOLOGY REVIEW

HYDROGEN FUEL CELL AND ELECTROLYZER END-OF-LIFE MANAGEMENT REVIEW

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ABSTRACT

Fuel cells and water electrolyzers are important components of a hydrogen value chain. The deployment of these devices and associated plant equipment will likely be rapid, and occur at large-scale, as energy systems decarbonize. Fuel cells and water electrolyzers generally pose end-of-life (EoL) opportunities and challenges similar to those for other advanced technologies and products. The industry needs to match the pace of deployment and implement EoL management systems before mid-life stack replacement and/or retiring this equipment.

This review provides a detailed overview of opportunities and challenges for EoL processing of fuel cell and water electrolysis components that are being deployed at a rapidly increasing pace and scale. Multiple types of commercially ready technologies are included, such as alkaline electrolyzers, proton exchange membrane electrolyzers, proton exchange membrane fuel cells, solid oxide electrolyzers, and solid oxide fuel cells. The review is limited to water electrolysis, hydrogen fuel cells, and critical balance-of-plant and auxiliary equipment. The review describes EoL concepts and hydrogen assets, EoL considerations for fuel cells and electrolyzers, availability of EoL providers and markets, and consortia actively addressing EoL research. Insights link opportunities and risks stemming from EoL management to related considerations for securing critical materials and reducing hazardous waste.

Various environmental, economic, regulatory, supply chain, and technological practices could reduce the life-cycle risks of deploying fuel cells and electrolyzers, including the following:

- Reduce use and increase recovery of critical materials
- Improve production and re-use processes for toxic and hazardous substances
- Improve design and recovery processes to address the challenges of supply chain logistics and complex components unsuitable for material separation
- Act quickly to deploy processes and infrastructure that enable the most effective waste management practices and invest in scaling more effective extraction processes
- Enact policies that motivate stakeholders in the value chain to implement EoL activities across all stages of product life
- Include EoL responsibility and clarify regulations and waste reduction targets in all purchase contracts

Keywords

Fuel cell
Electrolyzer
End of life
End-of-life
Recycling
Reuse

EXECUTIVE SUMMARY

uel cells and water electrolyzers are important components of a hydrogen value chain. The deployment of these devices and associated plant equipment will likely be rapid, and occur at large-scale, as energy systems decarbonize. Fuel cells and water electrolyzers generally pose end-of-life (EoL) opportunities and challenges similar to those for other advanced technologies and products. The industry needs to match the pace of deployment and implement EoL management systems before mid-life stack replacement and/or retiring this equipment.

This review provides a detailed overview of opportunities and challenges for EoL processing of fuel cell and water electrolysis components that are being deployed at a rapidly increasing pace and scale. Multiple types of commercially ready technologies are included, such as alkaline electrolyzers, proton exchange membrane electrolyzers, proton exchange membrane fuel cells, solid oxide electrolyzers, and solid oxide fuel cells. The review is limited to water electrolysis, hydrogen fuel cells, and critical balance-of-plant and auxiliary equipment. The review describes EoL concepts and hydrogen assets, EoL considerations for fuel cells and electrolyzers, availability of EoL providers and markets, and consortia actively addressing EoL research. Insights link opportunities and risks stemming from EoL management to related considerations for securing critical materials and reducing hazardous waste.

Major factors in the EoL management of fuel cells and electrolyzers are discussed within topic areas that include fundamental material properties, disassembly and material recovery, and lack of established value chains. Issues related to the use and reuse of critical materials are relevant for all commercial units manufactured today. Solid oxide systems present more complex EoL challenges than other technologies as no processes exist to support closed-loop reuse of the ceramics or the rare earth elements they contain. Various environmental, economic, regulatory, supply chain, and technological practices could reduce the life-cycle risks of deploying fuel cells and electrolyzers, including the following:

- Reduce use and increase recovery of critical materials
- Improve production and re-use processes for toxic and hazardous substances
- Improve design and recovery processes to address the challenges of supply chain logistics and complex components unsuitable for material separation
- Act quickly to deploy processes and infrastructure that enable the most effective waste management practices and invest in scaling more effective extraction processes
- Enact policies that motivate stakeholders in the value chain to implement EoL activities across all stages of product life
- Include EoL responsibility and clarify regulations and waste reduction targets in all purchase contracts

EoL management of fuel cells and water electrolyzers can provide significant benefits in three areas: circularity benefits, resource availability benefits, and environmental justice. In circularity, manufacturers secure the raw materials and then innovate to make their own products; reducing cost, supply, and control risks may motivate them to take on EoL process responsibility. To address limited resource availability (e.g., PGM, graphite, and cobalt), recovery and recycling of these materials from EoL products can provide alternative sources. Recovering materials from EoL equipment reduces the need to extract and refine raw materials and, provides an opportunity to consider moving the processing from particularly vulnerable communities, often in global locations, to those with more developed safety and environmental regulations.

Electric power companies and industry owners/operators can use this information to support their life cycle asset management and environmental stewardship activities. Reuse, recycling, and waste management industries can use this information to support creation of efficient, easy-to-use, and cost-efficient services that are well suited to technology owner needs. Research funding entities and policymakers can use the information to design programs to fill knowledge and technology gaps that will facilitate the presence of commercial EoL management infrastructure when the equipment is ready for processing after a lifetime of use.

Learning and engagement opportunities include:

- *Circular Economies for Energy Technologies Interest Group. Supplemental Project Notice.* EPRI, Palo Alto, CA: 2022. 3002025780.
- *EPRI Research Activities on Renewable and Battery End-of-Life Management.* EPRI, Palo Alto, CA: 2022. 3002019572.

ACKNOWLEDGMENTS

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PROJECT OBJECTIVES

Characterize current and potential future options for EoL management of fuel cells and electrolyzers to:

1. **Support electric power companies and industry owners/operators** in life cycle asset management and environmental stewardship, and
2. **Support reuse, recycling, and waste management industries** in creating efficient, easy-to-use and cost-efficient services well-suited to technology owner needs.

SCOPE OF THIS REVIEW

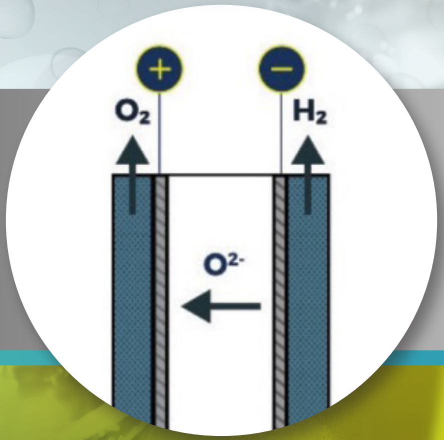
This work focuses on a subset of leading, commercial-ready fuel cell and water electrolysis technologies. It introduces material attributes from an EoL perspective and identifies management options, project life-cycle considerations, and applicable policies and regulations. The scope of this work is limited to:

- **Water electrolysis:** Commercially ready technologies of alkaline, PEM, and SOEC, with some comparison between material advantages of AEM versus PEM.
- **Hydrogen fuel cells:** Commercially ready technologies of PEM and SOFC.
- **Balance of plant (BoP) and auxiliary equipment** is included, but not investigated in detail. Critical BoP materials are also present in core fuel cell (FC) and water electrolyzer (WE) technologies, so they are addressed within this context. However, a more detailed analysis of BoP materials should not be neglected because these components and auxiliary systems use a substantial mass of materials (some classified as critical).

Many emerging technologies that are not included in this EoL review could result in significantly different conclusions as they do not contain the same materials or follow the same product assembly designs (for example, technologies that do not employ a membrane-based cell-to-stack architecture).

The material presented has been taken from published work and not yet been explored directly with key stakeholders, manufacturers, or waste management facilities. Currently, there is limited technical, social, and practical knowledge available on this topic. Markets and processes are not yet developed, and only a few large-scale R&D initiatives are focusing in this area. Additionally, most reports reference the same few sources. While the sources are of good quality, many were published five years ago, are limited in scope, and lack practical insights into EoL management processes. While current information is limited, deeper insights would not change the overall conclusions that the long-term success of the energy transition hinges on responsible use (and reuse) of materials. Future EPRI work on this topic will include interviews with key stakeholders and deeper assessments of the developing recycling and reuse technologies and evolving markets.

AN INTRODUCTION TO END-OF-LIFE CONCEPTS AND HYDROGEN ASSETS



END-OF-LIFE MANAGEMENT OF HYDROGEN EQUIPMENT

End-of-life (EoL) management of energy assets is a key owner/operator responsibility.

- Equipment, components, and materials deployed now require management when they come out of service.
- Technologies may contain trace amounts of valuable, critical,[1] and/or hazardous materials.
- The current lack of technologies designed for repair, refurbishment, reuse, repurposing, or recycling may increase costs or complicate logistics at EoL.
- Uncertainty in competitive reuse, repurposing, and/or recycling markets and policy support may be an issue when decommissioning.
- Opportunities exist for enhanced environmental and resource stewardship and financial recovery through EoL management.
- Energy companies want to understand how to drive opportunities through procurement requirements, purchasing decisions, and circularity actions.

1 The U.S. Department of the Interior defines critical materials as (1) those that "are vital to the Nation's security and economic prosperity" and (2) that the "dependency of the United States on foreign sources creates a strategic vulnerability for both its economy and military to adverse foreign government action, natural disaster, and other events that can disrupt supply of these key minerals" [1].

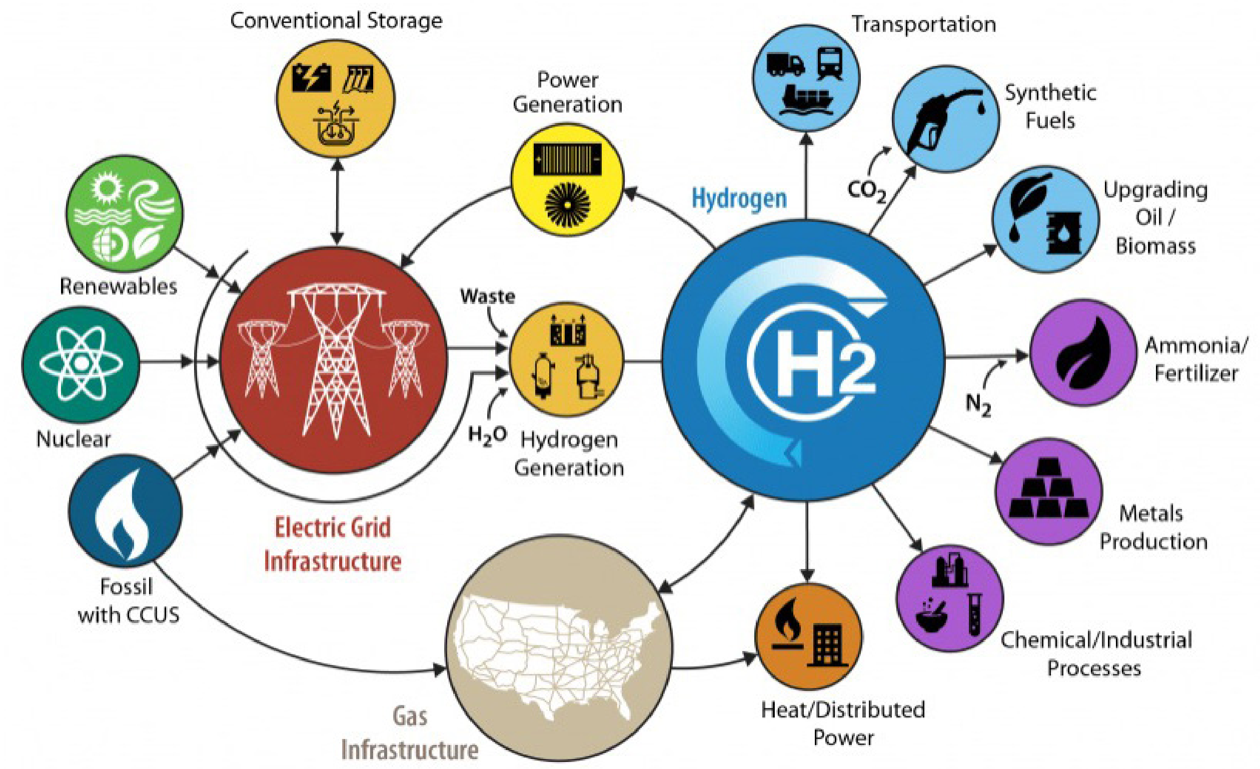
THE HYDROGEN VALUE CHAIN

The production and use of hydrogen rely on an extensive value chain consisting of multiple technologies. Fuel cell (FC) and water electrolyzer (WE) subsystems comprise a small fraction of the whole chain. However, the unique materials used in their construction indicate a need for EoL infrastructure to make the best use of resources such as critical materials and to minimize waste.

This review focuses on the following two systems of both FC and WE equipment:

- **Cell stacks and modules**
  - Includes the components of each cell
  - Groups cells into stacks
  - Assembles stacks into modules
- **The Remainder of the system**, including:
  - The housing for the modules
  - All other components of the FC/WE system
  - Associated balance of plant (BoP) equipment

The cell components contain the main materials of importance in EoL management. EoL is also a consideration for the system components and BoP, but these are typical for other steel-based industrial equipment and have more established EoL processes.



The hydrogen value chain, as shown in the H2@Scale U.S. Department of Energy (DOE) initiative, with FC and WE sub-components highlighted [2]

THE SCALE AND PACE OF FUEL CELL AND WATER ELECTROLYZER ADOPTION

The U.S. DOE estimates that meeting 2050 domestic market growth could require an electrolyzer capacity of up to 1000 GW.

The current U.S. planned and installed capacity is only 0.17 GW and would require a substantial 20% compound annual growth rate from 2021 to 2050 to reach the DOE's estimation.

The U.S. DOE also estimates a total domestic fuel cell capacity of over 50 GW, with an increasing domestic manufacturing rate of up to 3 GW/yr.

Other regions, including multiple countries in Asia, Oceania, and across the EU, forecast similarly sizeable growth estimates.

The scale and pace of projected growth emphasize the need for well-defined EoL processes and regulations to ensure a sustainable, cost-effective supply of materials across each region and reduce waste-related risks.

OVERVIEW OF HYDROGEN FUEL CELL COMPONENTS

Fuel cells (FCs) are electrochemical devices that convert chemical energy into electrical energy.

Four types of commercial FCs are suitable for use with hydrogen:

- Phosphoric acid (PAFC)
- Molten carbonate (MCFC)
- Solid oxide (SOFC)
- Proton exchange (or polymer electrolyte) membrane (PEMFC)

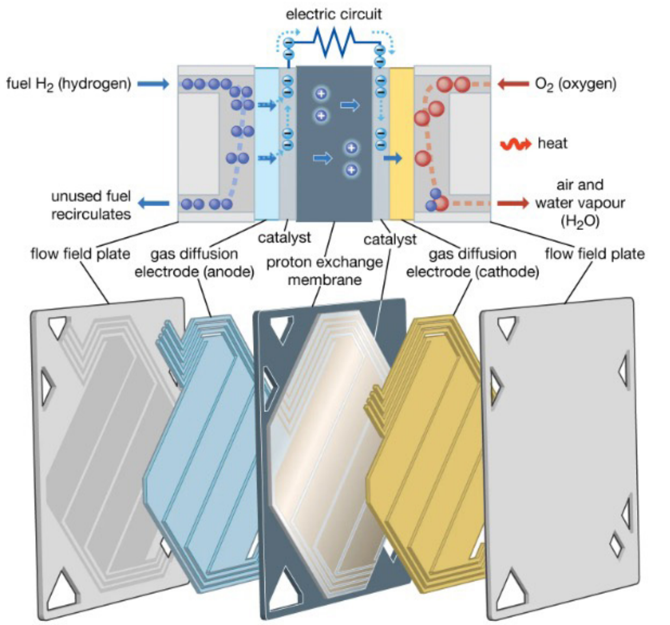
The general specifications of commonly used hydrogen fuel cells are shown in the table below [3].

SPECIFICATION TYPE	PAFC	MCFC	SOFC	PEMFC
Electrolyte	Phosphoric Acid	Molten Carbonate Salt	Ceramic	Polymer
Typical Operating Temperature (◦C)	190	650	1000	80
Fuel	Hydrogen (H_2) Reformate	H_2/CO Reformate	H_2/CO/CH_4 Reformate	Hydrogen (H_2) Reformate
Reforming Method	External	External/Internal	External/Internal	External
Oxidant	O_2/Air	CO_2/O_2/Air	O_2/Air	O_2/Air
Electrical Efficiency (%HHV)	40–50	50–60	45–55	40–50

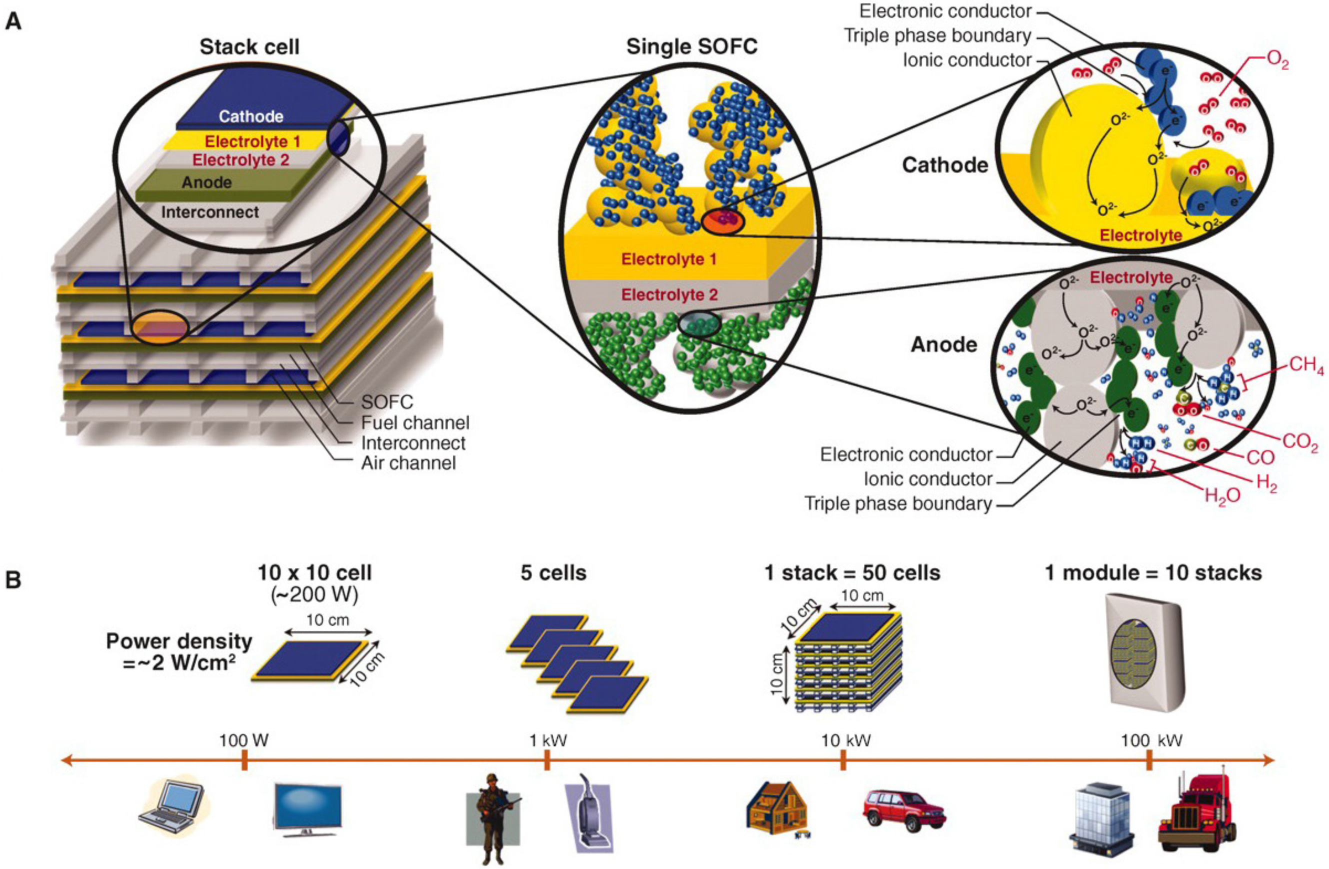
Overview of Hydrogen Fuel Cell Components (continued)

This EoL review investigates only two hydrogen fuel cell types, PEMFC and SOFC, which share many material similarities with electrolyzers of the same type (PEMWE and SOEC).

Detailed evaluations of FC technologies are in reports 3002026260 [4], 3002019891 [5], and 3002020540 [6].



PEMFC stack components and operation [7]



SOFC stack components (A) and general scale (B) for cells, stacks, and modules [8].
Reprinted with permission from AAAS.

OVERVIEW OF WATER ELECTROLYZER COMPONENTS

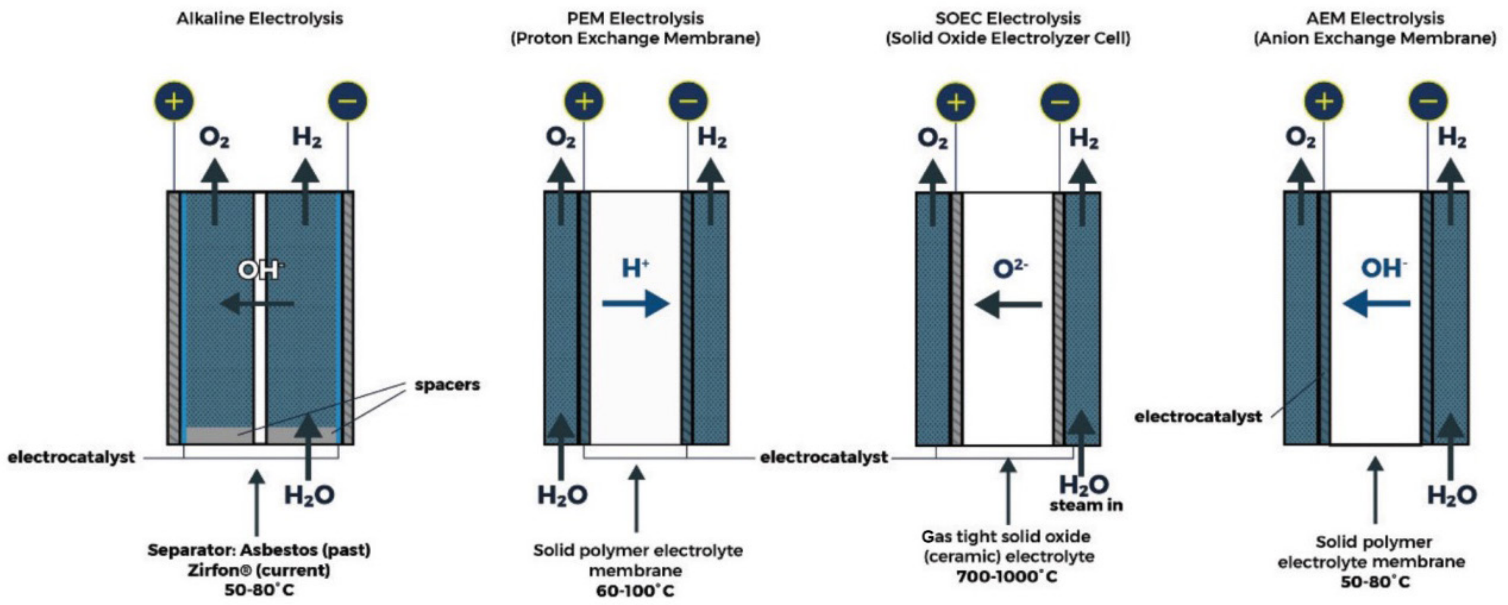
Water electrolyzers (WEs) are electrochemical devices that convert electrical energy into chemical energy.

The following four main types of water electrolyzers are suitable for hydrogen and commercially deployable now or in the near future:

- Alkaline (AWE)
- Proton exchange (or polymer electrolyte) membrane (PEMWE)
- Solid oxide (SOECWE)
- Anion exchange membrane (AEMWE)

This review investigates all four water electrolyzers. PEMs and AEMs share similarities in equipment design, but AEMs incorporate fewer critical catalyst materials. PEMWEs and SOECs share material similarities with FCs of the same type (PEMFC and SOFC).

Detailed evaluations of WE technologies are in EPRI reports 3002025148 [9], 30020263543 [10], and 3002027908 [11].



	ALKALINE	PEM	SOEC	AEM
Electrolyte	6M KOH, Zirfon (thick polysulfone)	H+ conducting polymer membrane (example: Nafion®)	Ceramics, for example, yttria stabilized zirconia (YSZ)	OH- conducting polymer membrane (often 0.1 – 1M KOH added)
Cathode	Ni, Ni-Mo Alloys	Pt, Pt-Pd	Ni/YSZ	Ni, Ni-Mo Alloys
Anode	Ni, Ni-Mo Alloys	RuO_2, IrO_2	LSM	Ni, Ni-Mo Alloys

The four electrolyzer cell types (top) and specialized materials used in each (bottom) [12]

RELEVANT MATERIALS AND COMPONENTS OF FUEL CELL AND WATER ELECTROLYZER STACKS

The table presents key materials used in the cells and stacks. The devices also incorporate other metals and polymers, shown subsequently.

- In **alkaline water electrolysis (AWE)**, the electrolyte is an aqueous solution of KOH, which is highly corrosive and limits the type of compatible materials. Electrodes are Ni-based, and the anode contains precious metal alloys.
- In **polymer electrolyte membrane/proton exchange membrane technology (PEMFCs and PEMWEs)**, the stack's core component is the membrane electrode assembly (MEA). The electrolyte is commonly a perfluorosulphonic acid membrane, and the electrodes contain platinum group metals (PGMs).
- In **solid oxide fuel cells (SOFCs)**, the electrolyte is a dense oxygen ion-conducting ceramic membrane separating two porous electrodes. Higher operatingtemperatures create restrictive conditions on the components.

FCH STACK	COMPONENT	MATERIAL	CRITICAL ASPECT[1]
SOFC	Andode	YSZ[2]	Cost; supply risk
		Ni; NiO	Hazard
	Cathode	$LaMnO_3$	Hazard; supply risk
	Electrolyte	YSZ	Cost; supply risk
	Interconnectors	Ni; NiO	Hazard
		$LaCrO_3$	Hazard; supply risk
PEMFC	Anode	Pt	Cost
	Cathode	Pt	Cost
	Electrolyte	Ionomer	Cost; hazard
PEMWE	Anode	Ir; Ru	Cost; hazard
	Cathode	Pt	Cost
	Electrolyte	Ionomer	Cost; hazard
	Bipolar plates	Ti	Cost
AWE	Anode	Ag	Cost
	Cathode	Ni; NiO	Hazard

Key materials used in the cells and stacks [13]:

1. *Multiple TechCycling reports identified critical aspects*
2 *YSZ: Yttria-stabilized zirconia*

MOTIVATIONS FOR END-OF-LIFE MANAGEMENT OF FUEL CELLS AND WATER ELECTROLYZERS [14, 15]

CIRCULARITY BENEFITS

Manufacturers secure the raw materials and then innovate to make their own products. Reducing risks (cost, supply, control) may motivate them to take on the responsibility for EoL processes. Due to the limited supply of critical minerals, many are sourced exclusively from politically unstable regions. Circularity would provide multiple benefits.

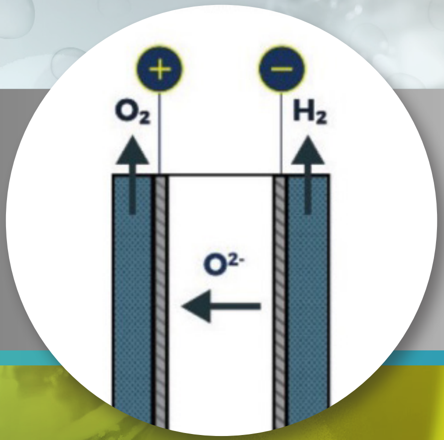
RESOURCE AVAILABILITY

A few countries supply almost all the key resources, such as PGM, graphite, and cobalt, which makes the supply chain vulnerable to disruptions. Recovery and recycling of valuable materials from EoL products represent a potential area of leadership and sourcing. Long lead times for permitting and the mitigation of associated environmental impacts present challenges.

ENVIRONMENTAL JUSTICE

Recovering materials through EoL equipment recycling and reuse can reduce the need to extract and refine raw materials. This can also shift material processing facilities from regions and communities more vulnerable to exposure to harmful materials to regions with more developed safety and environmental regulations, thus promoting environmental justice.

END-OF-LIFE CONSIDERATIONS FOR FUEL CELLS AND ELECTROLYZERS



REDUCING AND/OR REUSING MATERIAL INPUTS FOR FUEL CELLS AND WATER ELECTROLYZERS [16, 17]

In 2017, the HyTechCycling project surveyed 75 companies (54% manufacturers, 24% recycling centers, 16% end users, and 6% hydrogen associations) on EoL considerations. Insights from the **manufacturers** surveyed include the following:

- **Critical and hazardous material:** FCs and WEs require critical and hazardous materials.
  - 83% of manufacturers have reduced the quantity of hazardous materials (over an unspecified time frame).
  - 30% have reduced the quantity by at least 30%.
  - The remaining manufacturers all named material reductions a key future objective.
- **Reduction in weight and volume of the product:** Improved construction techniques (at the material supplier level) should be a priority over oversizing the component (at the component manufacturing level).
  - 34% stated they can reduce at least 30% of the total weight.
  - The remaining 66% stated they can reduce weight by 10–20%.

Manufacturers **should substitute materials with non-critical, less resource-intensive, and/or more readily recyclable alternatives** wherever possible. They can do so only if the substitution meets or exceeds the techno-economic metrics of the initial product or if new regulatory requirements come into force. The survey found only limited opportunities for material substitution in FCs and WEs at the time, and none were readily scalable to meet the expected rapid expansion in capacity over the next 10 years.

The most effective approach to reduce the risks associated with material supply and EoL recovery is to reduce the initial amount of material required for manufacture.

Reducing and/or Reusing Material Inputs for Fuel Cells and Water Electrolyzers *(continued) [16, 17]*

After elimination and substitution, the greatest opportunity stems from **using reclaimed or secondary materials in the manufacturing stage**. The direct reuse of cabinets, containers, and some BoP equipment can reduce raw material use and negative environmental impacts.

The 2017 HyTechCycling project survey gained the following further insights from the manufacturers:

- **Incorporation of used components:** Products should incorporate reused, repurposed, or recycled materials whenever possible.
  - 80% of manufacturers incorporated used materials in their products, with some already designing for used material in the manufacture of bipolar plates but not the stacks.
  - All stated they could incorporate used materials and still guarantee the reliability of the cells but noted significant challenges to incorporating used components across cell mounting and electrical components.
  - All stated they could incorporate used materials in the BoP components, which largely consist of steel (with the exception of control boards and some electrical components).
- **Design harmonization and standardization:** Products should be designed to simplify and optimize the dismantling and recycling processes to improve extraction effectiveness and reduce EoL costs.
  - 83% were interested in rethinking the design of their products to optimize the recycling and dismantling phases.
  - 100% agreed to standardize their fabrication process.

After elimination and substitution, the greatest opportunity stems from using reclaimed or secondary materials in the manufacturing stage.

MAJOR FACTORS IN THE END-OF-LIFE MANAGEMENT OF FUEL CELLS AND WATER ELECTROLYZERS

FUNDAMENTAL MATERIAL PROPERTIES

- The type (metal, ceramic, polymer, composite, and others) and amount of material used will have the largest impact on the product life-cycle and EoL processing requirements.
- Assuming EoL processes are available, the ability to reuse, repurpose, or recycle the material will depend on its properties.

DISASSEMBLY AND MATERIAL RECOVERY

- Even if the material can be recycled, the product's design will strongly impact the feasibility (technically and economically) of EoL processing.
- Most high-tech products have complex architecture and consist of hybrid composites, which make disassembly and extraction difficult or impossible.

ESTABLISHED VALUE CHAIN

- Beyond technical challenges, economic and social drivers are determining factors for the successful implementation of EoL processes.
- The availability of EoL processing infrastructure is a key enabler.
- Clear contracts and policies (alongside enforcement of waste management regulations) across all stakeholder groups are important.

END-OF-LIFE IMPLICATIONS STEMMING FROM MATERIAL PROPERTIES

Solid materials represent more valuable commodities than liquid and gaseous materials for manufacturing industries and include metals, polymers, ceramics, composite structures, and organics. FCs and WEs contain an advanced engineering mix of material types.

- **Metals** in bulk parts are commonly recovered and valorized. Stainless steel, copper, aluminum, titanium, and their respective alloys comprise the bulk of metal production and use. The sorting of metals such as aluminum or copper from titanium is challenging due to multiple separation steps, but the process is well developed at an industrial scale. While advanced metal components are recyclable, the processing steps require the elimination of organic, polymeric, and ceramic contamination from coatings and, often, large energy inputs to deconstruct alloys into single metallic species at high temperatures.
- **Ceramics** cannot normally be restored and reused in their original capacity, but they can be crushed down to particulate levels and reprocessed as additives if not mixed with metals or coated with polymeric materials. Chemical or thermal etching may be necessary to remove additives, which will generate liquid or gaseous waste streams.
- **Polymers** and commodity plastics represent a challenge stemming from the broad range of polymer types, which leads to large volumes of mixed waste material. Minor changes in contents or molecular weights may greatly affect the quality of the recycled products as well as the reproducibility of the recycling process. Further, polymeric materials are recyclable up to 10 times without degrading the molecular structure, after which they become unfit for further reprocessing.
- **Composites** can be of a homogeneous or heterogeneous type, and the complex nature of such materials makes them extremely difficult to dismantle and recycle cost-effectively. Electronics, or any other high-tech component, will contain several layers of metals, ceramics, and/or polymers mixed within a matrix. Such materials are not designed for recycling; the only processes deployed are for recovering valuable metals. The remainder of the composite is typically incinerated or sent to a landfill.

While technical processes are available, economic and social factors often drive the recycling rates of materials. Even with financial incentives, effective EoL processes rely on the availability of services and infrastructure and the implementation of enforceable waste management laws and regulations.

FLUORINATED POLYMERS [18]

Per- and polyfluoroalkyl substances (PFAS) encompass several thousand unique substances. They are widely used, long-lasting chemicals that break down very slowly. Because of their widespread use and persistence, PFAS have accumulated globally within the environment, food products, animals, and humans. Further, studies have linked exposure to some PFAS to harmful health effects. Because of these issues, authorities have begun to monitor and control PFAS exposure, with the European Commission proposing to ban all PFAS due to persistence, toxicity, and bioaccumulation risks.

Fluoropolymers (a subset of PFAS) are a specialty plastic that underpins the performance of many products used today, including FC and WE systems. The material properties of perfluorinated polymers are unique and impossible to replace in the near future. Restrictions on fluoropolymers, especially PTFE and ionomers with bound PFSA, would make deploying several key hydrogen technologies, such as WE, FC, and distribution systems, unfeasible.

The hydrogen value chain commonly uses fluoropolymers that fall into the OECD category of “polymers of low concern.”

- The most notable use is polymer-based membranes in PEM/AEM electrolyzers and PEM fuel cells. These require materials that provide conductivity, chemical stability, and mechanical strength. The best materials are ionomers that carry sulfonic acid groups (SO_3H), such as Nafion®, Forblue® S, Aquivion®, and 3M Corporation ionomers.
- PTFE (also called Teflon) is a component of membrane reinforcement and gas diffusion layers in low-temperature FCs and WEs, including PEM, AEM, and AWE.
- Estimates show that the total weight of a PEMFC stack can contain more than 10% fluorinated components. While technological advances can reduce cell thickness, substituting fluorine-free sealants would have the largest impact on reducing fluoropolymer mass. Estimates indicate that 1 GW of PEMFC capacity would require 44.3 tonnes of PTFE and 3.25 tonnes of ionomer (Nafion). In contrast, 1 GW of PEMWE capacity would require 12.5 tonnes of ionomer (due to thicker cells). PTFE used for sealing materials seems to generate the most cut-off waste, with up to 50% never making it into the final product.
- Other fluoropolymers, including ETFE, FFKM, FEPM, HFP, VDF, PFSA, and PTFE, are common components of gaskets, sealing materials, and other BoP equipment with hydrophobic and/or protective coatings.

***Fluorinated Polymers** (continued) [18, 19, 20]*

Most fluoropolymers used in FC and WE systems fall within the “low concern” category because they do not dissolve or contaminate water and cannot enter or accumulate in a person’s bloodstream. As with other industrial chemicals, manufacturing and EoL life cycle phases still pose risks. Based on published reports, some industrial groups, research groups, manufacturers, and environmental advocates working on hydrogen topics want regulations that limit PFAS-related exposure during manufacture and foster a robust EoL recovery effort for PFAS materials.

Risks and Waste During Production, Manufacture, and Use

- The production phase of fluorinated polymers poses the largest risk of exposure, as solvents are fluids, and the product has a low value at this stage. Once manufacturers mix the ionomer dispersion with precious metals, the product value significantly increases, and the likelihood of valuable losses decreases.
- The solid polymer used in manufacturing the membrane, support materials, sealants, and gaskets has a much lower risk for environmental release because it is a stable solid. While it is not a bioaccumulation risk, off-cuts can generate significant solid waste.
- During use, the polymer is sealed inside an engineered product and poses little risk of release. However, high temperatures and harsh chemical environments increase degradation risks, and industries are currently conducting assessments to verify the emissions risk as negligible.

Risks and Waste During Disposal

- Existing and emerging technologies to recover valuable and/or critical materials contained within fluorinated polymer composites typically require burning or chemical leaching. The most common process, incineration of the PTFE and/or ionomer, occurs in facilities that capture fluorinated compounds (HF) created by a reaction with calcium hydroxide to produce calcium fluoride, which is reused as a raw material.
- Academia and industry are developing and deploying many methods to recover and reuse the ionomers. The EU-based projects BReCycleEU and BEST4Hy aim to recover 70% of the ionomer. The Chemours Company, the largest producer of Nafion™ fluoropolymers and ion exchange membranes, also has ongoing research. Even if technologies emerge to recycle and recover ionomer components, broad deployment may require incentives or regulations dependent upon economics and other factors.

CRITICAL MATERIALS IN FUEL CELLS AND WATER ELECTROLYZERS

Many authorities periodically identify and evaluate "critical materials" or "critical raw materials," defined as substances used in technology that are subject to supply risks and for which there are no easy substitutes. Authorities use defined metrics to assess "criticality," which include the importance of securing the material, risks related to location-based supply sources, scarcity, and extraction and processing capabilities (which are more costly in regions with well-developed environmental regulations).[2]

While the total critical material mass used in FCs and WEs is small, associated negative environmental impacts (particularly in acquiring and processing raw materials) are sufficiently high to disproportionately impact the overall life cycle assessment.

In addition to FC and WE technologies, there has been substantial focus from governments and the public on various energy technologies arising from the need to source advanced materials at the start of life, unlike traditional fossil-based technologies that require fuel sourcing throughout their operational life. This shift from a "fuel-based" to a "material-based" energy system has prompted billions of dollars of investment in global infrastructure. The Inflation Reduction Act of 2022 (IRA) has provided for this investment in the United States.

Currently, the United States has no regulatory requirements governing the waste management of critical materials (beyond hazardous waste rules). Still, the issues here are highly visible and have driven some stakeholders to oppose the deployment of clean energy.

2 The U.S. Department of the Interior defines critical materials as (1) those that "are vital to the Nation's security and economic prosperity" and (2) that the "dependency of the United States on foreign sources creates a strategic vulnerability for both its economy and military to adverse foreign government action, natural disaster, and other events that can disrupt supply of these key minerals" [1].

Platinum

Graphite

Cobalt

Manganese

Nickel

Critical Materials in Fuel Cells and Water Electrolyzers (continued) [21]

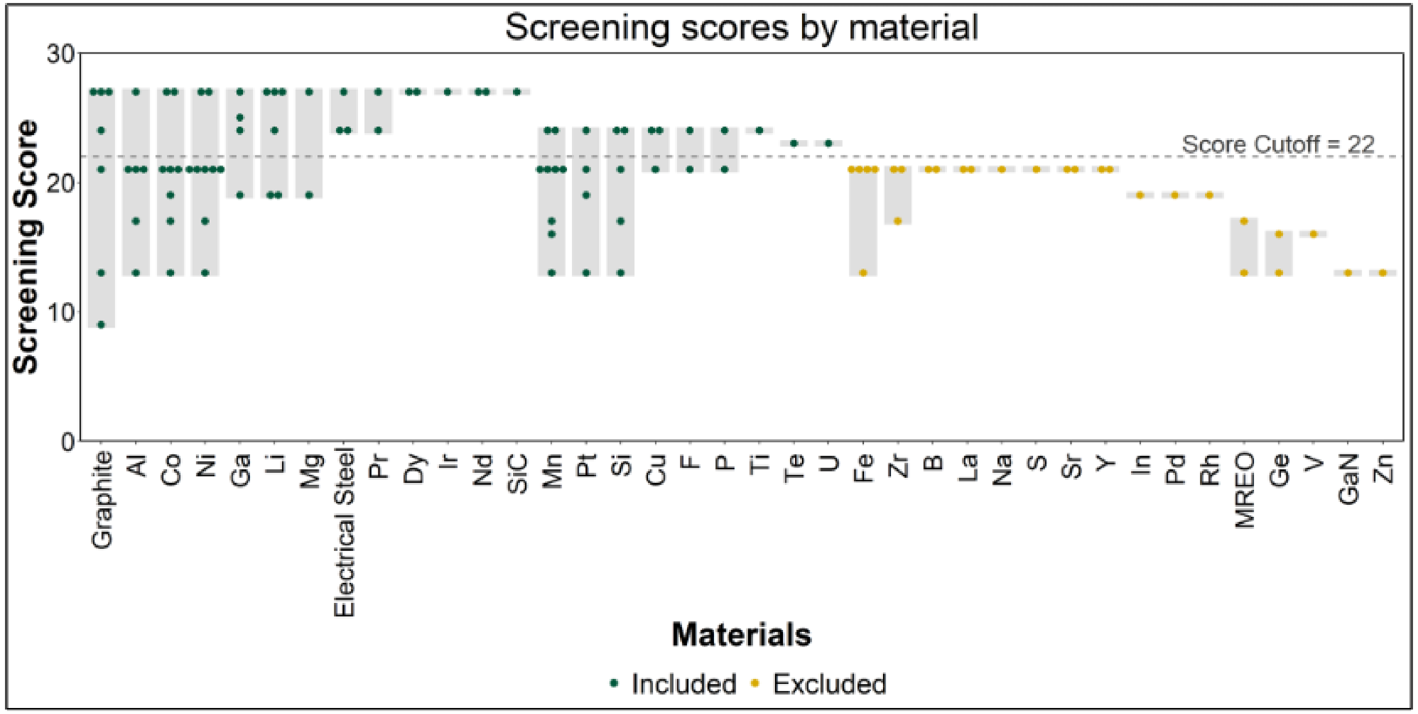
The 2023 U.S. DOE Critical Materials Assessment identified multiple materials as presenting a risk to FC and WE technologies. The table lists these materials, showing materials with a high score having higher risk.

- The assessment lists **six critical materials in the short term**, including cobalt, dysprosium, gallium, natural graphite, iridium, and neodymium.
- The assessment defines **nine near-critical materials**, including electrical steel, fluorine, lithium, magnesium, nickel, platinum, praseodymium, silicon carbide (SiC), and uranium.

The key materials used in FCs and WEs are listed below, with high-risk materials in bold:

- **Fuel Cells:** **Pt**, **Graphite**, La, Sr, **Co**, **Ni**, Y, Zr, and **Mn**
- **Electrolyzers:** **Pt**, **Ir**, **Ti**, La, Sr, **Co**, **Ni**, Y, Zr, and **Mn**

Critical materials are an important driver for EoL processes. Securing scarce materials through recycling reduces supply risks and can be cost-competitive and less resource-intensive than sourcing raw materials.



Critical Materials in Fuel Cells and Water Electrolyzers (continued)

Key Elements of PEMFC and PEMWE Supply

Raw Materials	Processed Materials	Subcomponents		End Product
	Perflourosulphonic acid (PFSA) - Nafion®	Electrolyte Membrane	Membrane Electrode Assembly (MEA)	PEM Fuel Cell and PEM Electrolyzer Cell Stack
	Sulfonated polyehter ether ketone (s-PEEK)			
	Polystyrene sulfonic acid (PSSA) (PEMFC)			
PGM (Pt)	Pt or Pt alloys	Cathode Catalyst		
PGM (Ir)	Ir or Ir-alloys (PEMEC)	Anode Catalyst		
Graphite (C)	Carbon metal oxide, carbides, etc. (PEMFC)	Catalyst Support		
Graphite (C)	Graphite composites (cathode GDL)	Gas Diffusion Layer		
Titanium (Ti)	Ti mesh/felt/foam			
Chromium, Nickel	Stainless steel metallic mesh			
Chromium, Nickel	Stainless steel (Ti-coated for PEMEC)	Bipolar Plates		
Titanium (Ti)				
Graphite (C)	Carbon fiber	End Plates		
Chromium, Nickel	Stainless steel			
Aluminum	Aluminum	Seal		
	Thermoplastic			
	Elastomer - Silicone, Viton or EPDM			

EOL Recovery

PEMFC
Platinum from membrane electrode assembly (MEA)

PEMWE
Platinum & Iridium from membrane electrode assembly (MEA)

Graphite, Titanium from bipolar plates (BPP)

Source: *The U.S. Department of Energy Water Electrolyzers and Fuel Cells Supply Chain [14]. This report focuses on the supply chains for two electrolysis technologies (PEMWE and SOEC) and two fuel cell technologies (PEMFC and SOFC).*

Critical Materials in Fuel Cells and Water Electrolyzers (continued)

Key Elements of SOFC and SOEC Supply

Raw Materials	Processed Materials		Subcomponents		End Product
Lanthanum (La)	LSM LSM-YSZ LSCF	Air Electrode Materials	Solid Air Electrode	Solid Oxide Cell	Solid Oxide Cell Stack
Strontium (Sr)					
Cobalt (Co)					
Iron (Fe)					
Manganese (Mn)					
Yttrium (Y)	8-YSZ	Electrolyte	Solid Electrolyte		
Zirconium (Zr)					
Nickel (Ni)	Ni-YSZ	Fuel Electrode Materials	Solid Fuel Electrode		
Stainless Steel	SS-441	Frame, Separator Plate, Electrode Flow Fields, End Plates	Cell Interconnects		
Borosilicate Glass	Boric Oxide Silica Glass	Spacers			

EOL Recovery
SOC Nickel from fuel electrodes, interconnects YSZ from spent electrolyte

Source: *The U.S. Department of Energy Water Electrolyzers and Fuel Cells Supply Chain [14]. This report focuses on the supply chains for two electrolysis technologies (PEMWE and SOEC) and two fuel cell technologies (PEMFC and SOFC).*

MATERIAL CRITICALITY OF ALKALINE WATER ELECTROLYZERS (EU PERSPECTIVE) [22, 23]

The table shows a basic materials list for alkaline WEs. The HyTechCycling criticality assessment for materials indicates high-risk materials in red.

AWE materials are typically low-cost, except for catalysts, which the EU classifies as critical.

The liquid alkaline electrolyte is classified as hazardous. Ni-based catalysts are carcinogens. Older AWE systems used asbestos diaphragms, which have been phased out to comply with regulations.

MATERIAL	MASS RATIO (%)
Carbon steel	71.54
Theroplastics	17.84
Nickel	10.60
Ruthenium	0.02

COMPONENT	MATERIAL	MATERIAL HAZARD	MATERIAL VALUE	SUPPLY CRITICALITY
Electrolyte	Potassium Hydroxide	Hazardous (corrosive)	Medium	Low
Anode	Precious metals	Non-hazardous	High	High
	Plastic	Non-hazardous	Low	Low
Cathode	Raney-Nickel	Hazardous (carcinogen)	Medium	High
	Plastic	Non-hazardous	Low	Low
Interconnect	Plastic	Non-hazardous	Low	Low
Sealant	Thermoplastic	Non-hazardous	Low	Low
	Elastomer	Non-hazardous	Low	Low
Diaphragm (Membrane)	Asbestos	Hazardous (carcingoen)	Low	Low
	Polymers	Non-hazardous	Medium	Low

The most critical materials are marked with red brackets.

MATERIAL CRITICALITY OF PEM FUEL CELLS (EU PERSPECTIVE) [22, 23]

The table shows a basic materials list for PEMFCs. The HyTechCycling criticality assessment for materials indicates high-risk materials in red.

Other than platinum (Pt), PEMFC materials are mainly low-to-medium in cost. Pt is one of the most critical materials for the EU states.

Most of the materials are non-hazardous.

MATERIAL	MASS RATIO (%)
Stainless steel	61.48
Aluminum	24.99
Carbon fiber	8.33
Tetrafluoroethylen	4.33
Carbon black	0.70
Platinum	0.14
Ruthenium	0.01

COMPONENT	MATERIAL	MATERIAL HAZARD	MATERIAL VALUE	SUPPLY CRITICALITY
Electrolyte	Perfluorosulphonic acid (PSFA)	Non-hazardous	Medium	Medium
	Sulfonated polyether ether ketone (s-PEEK)	Non-hazardous	Medium	Low
	Polystyrene sulfonic acid (PSSA)	Hazardous (corrosive)	Low	Medium
	Polybenzimidazole (PBI) doped with H_3PO^4*		High	Low
Anode and Cathode – GDL	Carbon cloth or paper treated with hydrophobic agent	Non-hazardous	Medium	Low
	Metallic mesh or cloth (e.g. stainless steel)	Non-hazardous	Low	Low
Anode and Cathode – Catalyst Layer	Platinum of Pt-alloys	Non-hazardous	High	High
	Catalyst support (carbon, metal oxides, carbides, etc.)	Non-hazardous	Medium	Low
Interconnect	Synthetic graphite or graphite composites	Non-hazardous	Low	Medium
	Stainless steel	Non-hazardous	Low	Low
Sealant	Thermoplastic	Non-hazardous	Low	Low
	Elastomer	Non-hazardous	Low	Low

The most critical materials are marked with red brackets.

** used only in high-temperatue PEMFC*

MATERIAL CRITICALITY OF PEM WATER ELECTROLYZERS (EU PERSPECTIVE) [22, 23]

The table shows a basic materials list for PEMWEs. The HyTechCycling criticality assessment for materials indicates high-risk materials in red.

PEMWE requires a larger number of more expensive critical materials than PEMFCs. Iridium supply is particularly concerning.

The materials are mainly non-hazardous, except for the anode catalysts.

MATERIAL	MASS RATIO (%)
Titanium	77.04
Stainless steel	14.59
Aluminum	3.94
Nafion®	2.33
Activated carbon	1.31
Copper	0.66
Iridium	0.11
Platinum	0.01

COMPONENT	MATERIAL	MATERIAL HAZARD	MATERIAL VALUE	SUPPLY CRITICALITY
Electrolyte	Perfluorosulphonic acid (PSFA)	Non-hazardous	Medium	Medium
	Sulfonated polyether ether ketone (s-PEEK)	Non-hazardous	Medium	Low
Catalyst layer – Cathode	Platinum of Pt-alloys	Non-hazardous	High	High
Catalyst layer – Anode	Iridium and Ir-alloys	Hazardous (irritant, harmful)	High	High
	Ruthenium and Ru-alloys	Hazardous (toxic, carginogen)	Medium	High
Anode and Cathode – GDL	Thermally sintered Ti	Non-hazardous	Low	Medium
	Ti or stainless steel mesh	Non-hazardous	Low	Medium
	Synthetic graphite or graphite composites (only possible on cathode side)	Non-hazardous	Low	Medium
Interconnect	Coated titanium or Ti-alloys	Non-hazardous	Low	Medium
Sealant	Thermoplastic	Non-hazardous	Low	Low
	Elastomer	Non-hazardous	Low	Low

The most critical materials are marked with red brackets.

MATERIAL CRITICALITY OF SOLID OXIDE FUEL CELLS AND WATER ELECTROLYZERS (EU PERSPECTIVE) [22, 23, 24]

The table lists basic materials for solid oxide FCs and WEs. The HyTechCycling criticality assessment for materials indicates high-risk materials in red. Note that it also classifies many materials as costly and hazardous.

Scandium, used in some SOFCs, has been considered a potential substitute for yttrium. However, scandium presents a greater supply risk and is not a sustainable alternative.

MATERIAL	MASS RATIO (%)
Stainless steel	61.44
Steel	21.09
Microporous insulation	10.91
Yttrium-stabilized zirconia	2.85
Nickel oxide	1.49
Lanthanum strontium manganate	1.31
Synthetic rubber	0.91
Copper	0.00

COMPONENT	MATERIAL	MATERIAL HAZARD	MATERIAL VALUE	SUPPLY CRITICALITY
Electrolyte	Yttria-stabilised zirconia (YSZ)	Non-hazardous	Medium	High
	Cerium gadolinium oxide*	Non-hazardous	Medium	High
Anode	Nickel-based oxide doped with YSZ	Hazardous (Cat. 1 carcinogen)	Medium	High
	Nickel	Hazardous (Cat. 1 carcinogen)	Medium	High
Cathode	Strontium-doped lanthanum manganite	Hazardous (Irritant)	Medium	High
	Lanthanum strontium cobalt ferrite*	Hazardous (Irritant)	Medium	High
Interconnect	Doped lanthanum chromate	Hazardous (Irritant, harmful)	Medium	Medium-High
	Inert metals/alloys	Non-hazardous	Medium	High
	Ferritic stainless steel*	Non-hazardous	Low	Low
Sealant	Glass/glass-ceramic	Non-hazardous	Low	Low
	Phyllosilicates (e.g., vermiculite, mica)	Non-hazardous	Low	Low
Substrate	Ceramic	Non-hazardous	Low	Low

The most critical materials are marked with red brackets.

** Materials added to the list after workshop in Brussels (26.9.2017).*

MATERIAL CRITICALITY OF BALANCE-OF-PLANT COMPONENTS (EU PERSPECTIVE) [22, 23]

Previous slides have shown the important material differences within the high-tech components across FC and WE types, particularly within the electrolyzer stack, due to material properties and manufacturing processes.

In contrast, within the BoP, most components are similar regarding material requirements across FC and WE facilities (compressors, water purification, dryers, and electrical systems).

The table lists the basic materials used across the BoP. The HyTechCycling criticality assessment for typical BoP configurations indicates no high-risk materials.

However, with the rapid deployment of renewable energy technologies and the expansion of the electricity infrastructure, the demand for specialty materials for use in the power system ancillary components may increase the supply risk for more materials needed in the BoP components shown here.

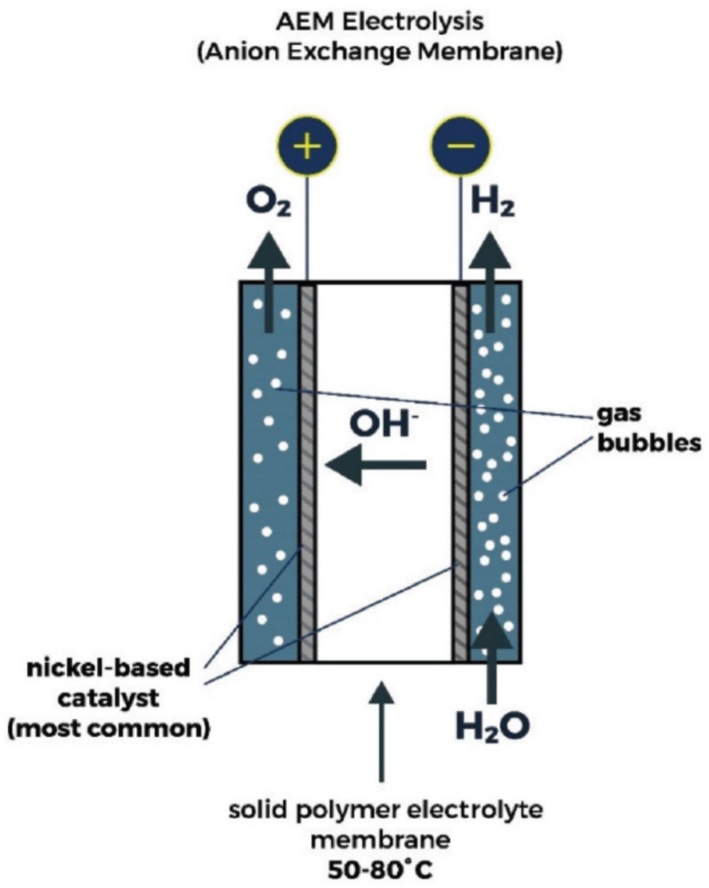
COMPONENTS		EOL WASTE
BoP components	Blower or compressor	Metals, plastics
	Humidification membrane	Metals, plastics, polymers
	Pumps	Metals, Teflon®, rubbers, plastics
	Regulators	Metals, plastics, rubbers
	Deionising filter	Metals, plastics, resins
	Pipes	Metals, plastics, rubbers
	Valves	Metals, plastics, nylon, Teflon®
	Gaskets (piping system)	Paper, plastics, rubbers
	Thermal insulation system	Mineral wool, fibreglass
	Heat exhangers	Metals
	Water condensers	Stainless steel
Ancillary BoP components	PCBs	Metals, plastics, semiconductors, precious metals
	Power conditioning system	Metals, plastics, semiconductors, precious metals
	Sensors	Plastics, precious metals, semiconductors, glass
Other components	Batteries	Plastics, Lithium-ion
	FCH external cabinet	Metal (ferrous material, aluminium, steel product...)

MATERIAL DIFFERENCES FOR EMERGING ANION EXCHANGE MEMBRANE WATER ELECTROLYZERS [16]

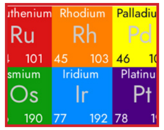
A novel type of WE system is based on anion exchange membranes (AEMs). This technology is in an early development phase and requires a genuine breakthrough to emerge as a serious contender alongside the other electrolysis options described previously. Developing a highly conducting, stable, and affordable AEM is the critical focus of research to date. While some AEM materials are commercially available, universities and R&D groups develop most of the materials in-house.

The basic concept is analogous to PEM technology, except that AEM materials conduct (hydroxide [OH-]) anions rather than protons, and, in theory, **this alkaline environment allows the use of non-precious metal catalysts.** The reactions in AEMWEs are the same as in AWEs; however, the polymer membrane in the AEM system allows for good separation of the hydrogen and oxygen gases, allowing for rapid startups and shutdowns and large operating windows, like those offered with PEMWEs. The baseline catalysts for AEM are nickel-based, with proposed designs using nickel-molybdenum, copper/cobalt, nickel/cobalt/iron, and nickel-iron alloys.

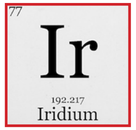
The main reasons to pursue AEM technology are the readily available, lower-cost catalyst materials it requires and the significant advantages it offers in product costs and sustainability. However, the development of this technology could negatively impact EoL drivers. If the use of expensive materials declines, motivation to invest in the high-efficiency EoL processes necessary to extract and reuse stack materials may, too.



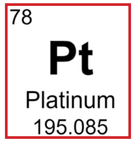
CONCLUSIONS ON HIGH-RISK FUEL CELL AND WATER ELECTROLYZER MATERIALS [14, 15, 25]



- Opportunities exist to prioritize research that further reduces PGM content and/or develops alternative catalysts for FCs and WEs.
- Avoiding the use of raw materials, especially PGMs, whenever possible will significantly reduce supply risks and negative environmental impacts.



- The presence of an iridium recycling infrastructure, end-of-life recycling rates of at least 90%, and low catalyst loading targets of 0.05 g/kW are important to meet future iridium demands for PEMWE, according to the U.S. DOE.
- An EU study found that the global iridium demand for PEMWE could become 470–1400% greater than the current global mining rate.



- PGM impacts are evident in all technologies but are more apparent in systems that include platinum because its extraction and processing cause greater environmental impacts.
- PEM technologies may necessitate more stringent EoL requirements than other FC and WE types.

- Materials for solid oxide WEs and FCs are identical or very similar. Effective EoL extraction and recycling are not available for these devices’ ceramics, rare earth elements, and nickel-based materials.

MAJOR FACTORS IN THE END-OF-LIFE MANAGEMENT OF FUEL CELLS AND WATER ELECTROLYZERS

FUNDAMENTAL MATERIAL PROPERTIES

- The type (metal, ceramic, polymer, composite, and others) and amount of material used will have the largest impact on the product life-cycle and EoL processing requirements.
- Assuming EoL processes are available, the ability to reuse, repurpose, or recycle the material will depend on its properties.

DISASSEMBLY AND MATERIAL RECOVERY

- Even if the material can be recycled, the product's design will strongly impact the feasibility (technically and economically) of EoL processing.
- Most high-tech products have complex architecture and consist of hybrid composites, which make disassembly and extraction difficult or impossible.

ESTABLISHED VALUE CHAIN

- Beyond technical challenges, economic and social drivers are determining factors for the successful implementation of EoL processes.
- The availability of EoL processing infrastructure is a key enabler.
- Clear contracts and policies (alongside enforcement of waste management regulations) across all stakeholder groups are important.

END-OF-LIFE MATERIAL RECOVERY PROCESSES FOR FUEL CELLS AND WATER ELECTROLYZERS [14, 15, 16]

- No guidelines currently exist for EoL processing of FCs and WEs. Further, only a handful of published comprehensive studies on the subject exist. The lack of clarity extends beyond FC- and WE-specific processes, as well-defined processes for recovering critical materials are generally rare. Other work EPRI has performed to evaluate FC technologies and PGM recovery has highlighted that a broad system for collecting critical materials at EoL does not yet exist and is not likely to develop in the near term.
- Given their economic relevance, PGMs such as platinum, iridium, and ruthenium are typically the targets of EoL technologies for FC and WE products. The PGM mass in PEM electrodes increases costs, so reducing the material used and increasing recovery rates should produce significant economic benefits. For PEM and other FC and WE types and their components, the economic feasibility will depend on the recovery efficiency and the initial concentration of precious materials.
- Material recovery from FCs and WEs at EoL has specific environmental drivers. Ni and Raney-Ni are hazardous materials present in electrocatalyst materials and other components. Landfills restrict the disposal of these materials, and reliable EoL controls are required. More regulated controls on the production, usage, and disposal of PFAS materials are rapidly being deployed.
- Given the prevalence of PGMs and nickel in many products, hydrometallurgical and pyrometallurgical recovery treatments for these materials are widely available. Unlike hydrometallurgical processes, pyrometallurgical processes present higher recovery efficiency but require a higher energy demand. Hydrothermal recovery treatment is another well-known method that could be applicable for the recovery of YSZ from SOFC sand SOECs.
  - **Hydrometallurgical method:** involves the dissolution of target elements from solid matrices through acid or caustic attacks. The benefits of this method are a high selectivity to metals, relatively low energy consumption, and the possibility of recycling reactants. This method's downside includes mechanical pre-treatment to increase exposed surface area, using a large volume of solutions, and generating corrosive and/or toxic wastewater.
  - **Pyrometallurgical method:** involves a calcination process that incinerates membranes and electrodes. Acid dissolution processes the ashes from combustion, and metal target elements are later recovered via precipitation.
  - **Hydrothermal treatment:** involves using high temperature and pressure steam to extract target elements.
- While recovering the lanthanum-based materials in SOFCs and SOECs would also be beneficial, no EoL processes are currently available to recycle them with suitable purity.

END-OF-LIFE OPTIONS FOR MATERIALS USED IN ALKALINE WATER ELECTROLYZERS [26]

- This table identifies best-case EoL processes that could enhance material recovery across the full AWE system. Much higher material losses than those anticipated here could occur.
- Two main products are recoverable from AWE stacks: nickel and common plastics.
- For nickel, a hydrometallurgical process treats the spent Raney-Ni catalyst.
- The treatment process for common plastics grinds the PTFE scrap into fine powder and blends it with pure PTFE for use as a recycled material in new products.

MATERIAL TYPE	DESCRIPTION OF MATERIALS	MASS INPUT, KG	EOL PROCESS	RATE
Steel	Carbon steel, stainless steel, cast iron	2698.05	REC	88%
Carbon	Black carbon	3.53	EE	100%
Non-Ferrous Materials	Aluminum	267.40	REC	96%
Plastics	TM	517.99	REC	100%
	Brass	3.70	REC	100%
	TM	0.18	REC	30%
	Bronze	0.05	LF	100%
	Copolymer	46.20	EE	100%
	Polyester	25.43	EE	100%
	Thermoplastics	215.05	REC	84%
	PVC	26.96	LF	100%
	Polypropylene	24.64	REC	84%
	EPDM	0.05	EE	100%
	NBR	0.16	EE	100%
	Polyurethane	1.12	EE	100%
	ABS	0.83	EE	100%
	Polyamide (PA)	0.35	EE	100%
PGM	PGM	0.13	REC	50%
	PGM	0.017	REC	90%
TM Metals	TM	60.00	REC	92%
Others	Glass	1.06	LF	100%
	Ceramic	31.35	LF	100%
	Silica	53.80	LF	100%
Excluded	OH steel for container	5627.1	RU	–
	Fluorescent lamp	42.32	RU	–
	Exterior paint	165.06	RU	–

Legend: *RU – reuse, REC – recycled, EE – energy extraction, lf – landfilled, nd – no data*

END-OF-LIFE OPTIONS FOR MATERIALS USED IN PEM FUEL CELLS [14, 26]

- This table identifies best-case EoL processes that could enhance material recovery across the full PEMFC system. There can be much higher material losses than those anticipated here.
- In PEMFC, the main drive is to recover and recycle critical stack materials. Recovery currently uses the following two methods.
  - A hydrometallurgical process recovers PGMs from the catalyst layer.
  - A pyrometallurgical process incinerates the membrane, GDLs, and electrodes. The ashes are then processed through dissolution, and PGMs are precipitated.
- **Bipolar Plates:** Alteration of the physical and chemical structure of bipolar plate materials during operation limits reuse or recovery for the same original application. However, materials may be suitable for reuse in other devices.

MATERIAL TYPE	DESCRIPTION OF MATERIALS	EOL PROCESS	RECOVERY RATE
Steel	Steel (carbon steel, stainless steel, iron)	REC	88%
Non-Ferrous Materials	TM	REC	100%
	Aluminum	REC	96%
	Lead	REC	65%
Plastics	PBI	EE	100%
	Acrylonitrile-butadiene-styrene part (ABS)	EE	100%
	Ethylene proplyene diene elastomer (EPDM)	EE	100%
	Polyester	EE	100%
	Polypropylene	REC	84%
	Polyurethane (PU) [Plastics]	EE	100%
	Polyvinylchloride	LF	100%
	Styrene acrylonitrite (SAN)	REC	84%
	LLDPE	REC	84%
Electronics	Electronics	EE	100%
Others	Carbon	EE	100%
	Synthetic graphite	EE	100%
	PTFE, Viton®, Silicone	LF	100%
	Ceramics	LF	100%
	PFTE	LF	100%
	Insulation Material	LF	100%
	Triethylene Glyol (Coolant)	REC	100%
PGM		REC	76%
Critical	PM	REC	90%
Reuse	Steel Cabinet	RU	100%

Legend: *RU – reuse, REC – recycled, EE – energy extraction, LF – landfilled, ND – no data, TM – transition metals, PGM – platinum group metals, PM – precious metals*

END-OF-LIFE OPTIONS FOR MATERIALS USED IN PEM WATER ELECTROLYZERS [14, 26]

- This table identifies best-case EoL processes that could enhance material recovery across the full PEMWE system. There can be much higher material losses than those anticipated here.
- EoL options for PEMWE stack materials are very similar to PEMFCs. Existing and novel EoL technologies can recover critical materials, including iridium, through existing (hydrometallurgical and pyrometallurgical) or novel (transient dissolution) methods.
- **Bipolar Plates:** Recovery of titanium from the alloys used for bipolar plates requires more complex processes than those necessary for pure titanium products.

MATERIAL TYPE	DESCRIPTION OF MATERIALS	MASS, KG	EOL PROCESS	RECOVERY RATE
Steel	Carbon steel, stainless steel, cast iron	2167.006	REC	88%
Non-Ferrous Materials	Aluminum	265.335	REC	96%
	TM	567.949	REC	100%
	Brass	16.14225	REC	100%
	TM	0.18	REC	30%
	Bronze	1.35	REC	100%
Plastics	Polypropylene	9.741665	REC	84%
	Polyester	0.9365	EE	100%
	Poly Ethylene	0.161	REC	84%
	Thermoplastics	103.7458	REC	84%
	PVC	10.65	LF	100%
	PEEK	11.148	EE	100%
	Polyamide	2.375	EE	100%
	EPDM	0.179	EE	100%
	ABS	0.42	EE	100%
	Polyuretane	1.12	EE	100%
	NBR	0.11	EE	100%
PGM	PGM	0.100359	REC	76%
TM	TM	36.6548	REC	40%
Others	Silica	32.7	LF	100%
	Ceramics	31.35	LF	100%
	Glass	0.65	LF	100%
	PFTE	0.464	LF	100%
	PVDF	0.3	LF	100%
Excluded	Steel container	5520.1	RU	–
	Paint	165.06	RU	–
	Fluorescent lamp	42.32	RU	–

Legend: *RU – reuse, REC – recycled, EE – energy extraction, lf – landfilled, nd – no data*

END-OF-LIFE OPTIONS FOR MATERIALS USED IN SOLID OXIDE FUEL CELLS AND SOLID OXIDE ELECTROLYSIS CELLS [14, 26]

- SOFCs are constructed from ceramic materials. The high-temperature operation of SOFCs promotes the migration of chemical species, and the presence of trace contaminants leads to significant performance degradation. Thus, the implementation of closed-loop ceramic waste recycling processes is impracticable. Reusing ceramic materials in other applications is possible, such as in the construction industry, where ceramic materials are a potential replacement for clays and minerals in manufacturing cement and concrete. The economic value of ceramics used as construction materials does not compare with that of high-tech applications like SOFCs.
- Currently, recycling processes are non-existent to support EoL management and secure the rare-earth elements of SOFCs and SOECs, and information on EoL processes for most materials in the SOFC technology is lacking.
- A proposed recovery route for the anode catalysts in SOFCs and SOECs is a hydrometallurgical process to react nickel oxide with sulfuric acid to form nickel sulfate, similar to the process used with AWEs. This method is also applicable for nickel recovery from the interconnects.
- SOFCs with a planar cell design can support recycling the steel interconnect plates by hydrothermal processes.
- Initial tests indicate that hydrothermal processes can recover YSZ from spent electrolytes, but the resulting material is only suitable for products with lower purity requirements than FCs and WEs. Due to the economic value and weight contribution of YSZ, more suitable recovery and recycling strategies are necessary. The only other option is to grind and separate the ceramic composite for low-value construction applications.
- The greatest benefit of recycling stems from the recovery and recycling of the cathode material, strontium-doped lanthanum manganite (93% of weight contribution within the tubular SOFC stack). No recovery process is currently available for lanthanum compounds (LSM and LSCF), and due to their hazardous nature, they require disposal in hazardous waste landfills.
  - While the cathode material has the greatest environmental impact and economic value, EoL options are currently limited because the cathode material is uncommon and recycling processes are not developed or available.
  - Assuming that cathode materials cannot be substituted, future guidelines to recycle critical SOFC materials will be important for EoL strategies to support the commercial deployment of SOFC technology.

THE DEVELOPMENT OF END-OF-LIFE TECHNOLOGIES FOR FUEL CELLS AND WATER ELECTROLYZERS [13]

Most current research on EoL technologies for FC and WE components focuses exclusively on PGM recovery. Criticality assessments support this recovery as key for industry sustainability. However, more research should address the recovery of other relevant materials. Other than ionomers, there does not appear to be much, if any, investment in developing and deploying novel technologies to recover other pertinent materials.

- Novel technologies under development to recover PGMs:
  - **Selective electrochemical dissolution (SED):** Allows the recovery of both the carbon support and the Pt catalyst from FC MEA. This method facilitates the recovery of high-purity catalysts at relatively mild conditions (pH, temperature, voltage) and offers suitable techno-environmental performance.
  - **Transient dissolution (TD):** A method based on the acid dissolution of Pt for its recovery. The key advantages are the avoided use of external potential, high recovery yield, and mild operating conditions. Recovery of other materials (such as the membrane and catalyst support) is not an option. By adjusting the reaction conditions, this method may also recover other metals (including Ru, Ir, and Pd in PEMWE and AWE).
  - **Acid process (AP):** Allows for the efficient recovery of both the PGM and ionomer by using strong acids to oxidize the carbon support, followed by separation steps. One of the main features is the possibility of regenerating a high-performance membrane directly integrated into new stacks. Drawbacks are harsh pH conditions and a complex, long-duration process.
  - **Alcohol dissolution (AD):** A solvent process that addresses the recovery of ionomers and noble metals from PEM components. A microwave heater controls the process by adjusting residence time and temperature. This method employs mild conditions (pH, temperature, and voltage) but raises economic feasibility concerns. Recycling solvents could reduce costs.

The following slide shows a comparison of these and existing methods.

A COMPARISON OF END-OF-LIFE TECHNOLOGIES FOR FUEL CELLS AND WATER ELECTROLYZERS [13, 27]

The available and in-development processes for PGM recovery described on previous slides are compared. The table highlights insights on EoL processes for FC and WE cells gained through the HyTechCycling project, with some major challenges circled in red.

PROCESS	WORKING CONDITIONS	REACTANTS	ENERGY REQUIREMENTS		CATALYST RECYCLING YIELD	FURTHER RECOVERED MATERIALS	DURATION
			HEAT	ELECTRICITY			
SED	Harsh (T)	$HClO_4$, O_2, HCl	–	Moderate	~90%	C support	3-5 h
TD	Mild	NaCl, HCl, CO, O_3	–	–	~90%	–	~3h
AP	Harsh (pH)	H_2SO_4, NaOH, Cu	Moderate	High	> 94%	Ionomer	>80h
AD	Mild	Alcohol and water	–	Moderate	~90%	Ionomer	< 1h
PMT	Harsh (pH, T)	Acids, HCl, NaOH, HNO_3	High	–	~90%	–	~10h
HMT	Harsh (pH)	Oxidants, HCl, NH_4Cl, NaOH	–	–	< 80%	–	>24h

A Comparison of End-of-Life Technologies for Fuel Cells and Water Electrolyzers *(continued) [13, 27]*

The HyTechCycling project published a SWOT analysis of each method's technical, economic, environmental, social, and regulatory aspects. This led to the conclusion that a straightforward identification of definitive EoL processes was not yet feasible.

Conventional technologies present several limitations and concerns. Novel technologies promise enhanced recovery and/or environmental features but are not yet developed at scale.

These studies are five years old, and the technology has likely progressed. Other projects are underway, and many entities are investing in this area.

Strengths		Weaknesses		Opportunities		Threats	
PMT	S4, S10, S11, S12, S14	PMT	W1, W2, W3, W5, W7, W9, W10	PMT	O4, O5	PMT	T1, T2
HMT	S1, S2, S7, S10, S11, S14	HMT	W3, W4, W6, W9	HMT	O4, O5	HMT	T1
HTH	S10, S11, S13	HTH	W1, W3, W6, W7	HTH	O1, O5	HTH	T4
AP	S4, S5, S9, S10, S14	AP	W1, W2, W3, W6, W7, W9, W10	AP	O2, O4, O5	AP	T1, T2, T4
SED	S1, S4, S5, S6, S8, S14	SED	W7, W9	SED	O2, O3, O4, O5	SED	T3, T4
AD	S2, S3, S4, S5, S6, S9, S13	AD	W1, W7, W8	AD	O1, O2, O3, O4, O5	AD	T3, T4
TD	S1, S3, S4, S6, S10, S13, S14	TD	W9	TD	O1, O2, O4, O5	TD	T1

S1: Low investment costs
S2: Low operating costs
S3: Mild operating conditions
S4: High recovery efficiency
S5: Recovery of more than one material
S6: Fast process
S7: Low energy requirements
S8: Low complexity
S9: Toxic compound removal
S10: Versatile technology
S11: Mature technology
S12: Co-processing of material from different sources
S13: Low environmental concerns
S14: High potential for reuse in high-value application

W1: High investment costs
W2: High operating costs
W3: Harsh operating conditions
W4: Low recovery efficiency
W5: Applicable to only one type of material
W6: Lengthy process
W7: High energy requirements
W8: Low-value product
W9: Use of hazardous reactants
W10: Significant environmental concerns

O1: Potential economic incentive for eco-friendly techniques
O2: Potential breakthrough in technology
O3: Anticipated fulfilment of future circular economy targets
O4: High deployment of FCH technologies
O5: High social demand of green market

T1: More severe regulations on hazardous materials
T2: More severe restrictions on emission levels
T3: FCH deployment rules out by policy-makers
T4: Increased electricity prices

Legend

PMT	Pyro-hydrometallurgical process	AP	Acid process	TD	Transient dissolution
HMT	Hydrometallurgical process	SED	Selective electrochemical dissolution		
HTH	Hydrothermal treatment	AD	Alchohol dissolution		

MAJOR FACTORS IN THE END-OF-LIFE MANAGEMENT OF FUEL CELLS AND WATER ELECTROLYZERS

FUNDAMENTAL MATERIAL PROPERTIES

- The type (metal, ceramic, polymer, composite, and others) and amount of material used will have the largest impact on the product life-cycle and EoL processing requirements.
- Assuming EoL processes are available, the ability to reuse, repurpose, or recycle the material will depend on its properties.

DISASSEMBLY AND MATERIAL RECOVERY

- Even if the material can be recycled, the product's design will strongly impact the feasibility (technically and economically) of EoL processing.
- Most high-tech products have complex architecture and consist of hybrid composites, which make disassembly and extraction difficult or impossible.

ESTABLISHED VALUE CHAIN

- Beyond technical challenges, economic and social drivers are determining factors for the successful implementation of EoL processes.
- The availability of EoL processing infrastructure is a key enabler.
- Clear contracts and policies (alongside enforcement of waste management regulations) across all stakeholder groups are important.

CURRENT STATE OF FUEL CELLS AND WATER ELECTROLYZER END-OF-LIFE OPTIONS

STRATEGIC DEVELOPMENT

While some manufacturers will take back equipment for EOL processing, there still exists a lack of specific reuse, repurposing and recycling strategies for most materials and components [23].

GLOBAL CONSIDERATIONS

Due to the complex components and skills required, alongside international market drivers, deployment of EoL processes is likely to depend on a global supply chain.

Thus, EoL processes should consider specific national policies and regulations stemming from transboundary critical material and waste movement.

SUPPORT NEEDED

Manufacturers need support and incentives to:

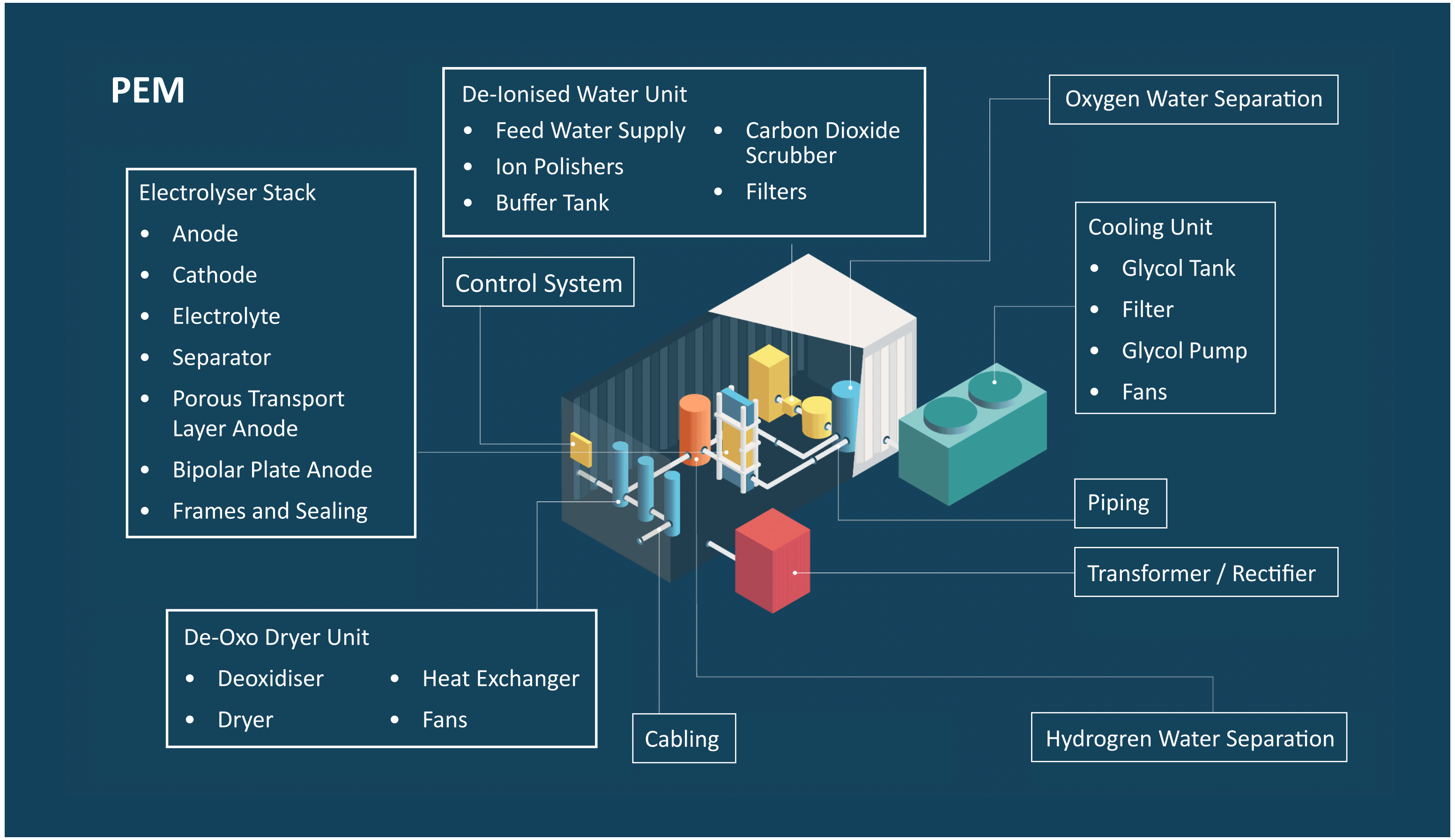
- Maximize the recovery and reuse of critical materials
- Redesign products to enable greater compatibility with dismantling, reuse, and recycling

End users need infrastructure and incentives to ensure collaboration and application of an EoL logistics framework.

Waste management processes need innovation, investment, infrastructure, and incentives to recover and reuse materials deployed in FCs and WEs (including and beyond PGM).

MATERIALS SUPPLY CHAIN FOR PEM WATER ELECTROLYZERS

The complexity of materials and stakeholders required to construct FC and WE facilities is significant. The figure shows an example PEMWE facility to highlight the number of sectors involved.



The materials supply chain to support construction of a PEMWE facility, including BoP components [28]

END-OF-LIFE MARKET OPPORTUNITIES

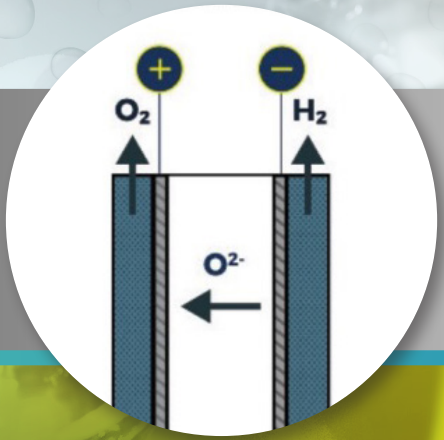
- Because this review projects that most FC and WE developments will be large-scale, skills developed in other decommissioning sectors, like renewables and energy storage, can apply. Industrial-scale waste management is much easier to implement and control than highly distributed goods, such as consumer products.
- Due to the high cost and critical nature of the materials involved, EoL processes can help alleviate high material demand (a key vulnerability in the supply chain) and reduce risk. Cost reduction opportunities will increase as the industry scales.
- While the FC and WE value chains are global, developing regional hydrogen hubs with co-located materials, equipment, capabilities, and infrastructure should de-risk some supply chain requirements by linking materials and manufacturing with operational and EoL stakeholders.
- Several regions, including the EU, have already been considering EoL concepts for some time. Thus, policies, incentives, and technologies could be ready for implementation within the next 10 years and coincide with rapid FC and WE deployment. Other regions may leverage these insights and develop their own market strategies.

END-OF-LIFE MARKET CHALLENGES

EOL market challenges include the following:

- Marketing will require coordination among users, manufacturers, and waste management companies, all of whom may have competing drivers and not be regionally co-located.
- Complex architectures and artifacts from the original manufacturing process complicate the extraction and re-processing of the materials.
- Not all materials are reusable in FC or WE applications, creating a need to identify other cost-effective applications and customers for the materials.
- The market faces a current lack of logistics to support widespread EoL management; some approaches do not yet have commercially ready technologies.
- A critical mass of recyclable material should accumulate before EoL service providers will be willing to expand their capacity.
- Limited policies are in place to motivate all stakeholders to plan and execute EoL management activities.
- EoL providers are unsure they can achieve profitability by implementing reuse, repurposing, and recycling processes.

THE AVAILABILITY OF END-OF-LIFE PROVIDERS AND MARKETS



STIMULATING MARKETS AND MOTIVATING END-OF-LIFE PROVIDERS

In 2017, the HyTechCycling project surveyed 75 companies (54% manufacturers, 24% recycling centers, 16% end users, and 6% hydrogen associations) on EoL considerations.[3]

- Of the **manufacturers** surveyed, 100% were interested in sourcing recycled materials for reuse, 30% had workstreams focused on EoL management, 60% had experience collecting devices at EoL, and 60% had already established EoL-related contracts with users, suppliers, and/or waste management facilities.
- Of the **recycling centers** surveyed, 50% had the technology required for the recovery of critical materials (HTM or PMT), 84% said they would accept FC/WE waste (regardless of their processing capability), 60% would consider investing in technology to improve recycling of FC and WE equipment, and 40% suggested distribution of FC and WE components across multiple, specialized waste management facilities.
- Of the **end-users** surveyed, 67% have considered the EoL requirements of their FC/WE assets, 80% named sending equipment and components back to the manufacturer as the best approach, 20% have managed FC and WE EoL processes by returning equipment to the manufacturer as outlined in the initial contract, 100% were interested in specific agreements with manufacturers and recycling centers to define and coordinate EoL logistics.
- **All three groups were interested in establishing "agreements" to support EoL processes, including the following:**
  - Agreements between manufacturers and recycling centers to ensure the correct management of the waste and enable investments in new technologies for the longer term
  - Agreements between manufacturers and recycling centers to stabilize cash flows and improve economic returns through the manufacturers' purchase and reuse of the recovered materials
  - Agreements between manufacturers and end users to incentivize cooperation and ensure the return of equipment at EoL
  - Agreements framed among end users, manufacturers, and recycling centers to establish EoL processes and logistics that secure materials and intellectual property within a membership group

3 **Source:** HyTechCycling EU Fuel Cells and Hydrogen Joint Undertaking Results analysis of the questionnaires to FCH manufacturers, recycling centers, distributors, and end users, 2018 [17]. This survey was conducted over five years ago, and the hydrogen landscape has evolved significantly since that time.

CURRENT LEADERS IN END-OF-LIFE PROCESSES FOR FUEL CELLS AND WATER ELECTROLYZERS

Some providers, such as Johnson Matthey, are actively developing closed-loop supply chains.

- As the largest secondary PGM refiner[4] in the world, they have developed highly advanced processes to extract and separate PGMs
- Currently operating full refine-supply cycles with refining capabilities for seven precious metals
- Ability to refine PGMs to a purity of 99.95%
- Technical support teams working directly with customers to optimize precious metals recovery from complex materials.
- International support through operations in Europe, North America, and Asia

4 Secondary refining removes impurities and finalizes the product, focusing on recovering materials from scrap and salvage. This compares to primary refining, which produces bulk metals from ore.

THE CURRENT STATE OF THE END-OF-LIFE VALUE CHAIN FOR FUEL CELLS AND WATER ELECTROLYZERS

Fuel Cell Manufacturers **with** Established EoL Processes [29]

EPRI previously interviewed manufacturers and material suppliers to gain insights into the current EoL processes deployed within the FC value chain. The first step was to determine fuel cell manufacturer takeback policies.

FC manufacturers with established EoL processes: Many well-developed manufacturers, such as Johnson Matthey and Nel Hydrogen, thought the desire for material recovery would organically drive high FC takeback rates with no need for incentives or regulatory action. They also shared insights into their current processes.

- EoL activities focus on the cell stacks because of the large concentration of high-value materials and because those components have the highest intellectual property value. When accepting EoL products for processing, whether customer products or manufacturing scrap, the method was relatively straightforward because extensive documentation on the specifications, capacity, and MSDS, as well as compositional information taken during production, installation, and maintenance activities, existed. Current return and evaluation processes began with a standard return authorization of materials (RMA) process.
- Because the stack is under a high mechanical sealing load and requires special tools for safe disassembly, customers are reluctant to attempt the disassembly themselves. Internal guidelines govern the disposition of the various stack parts (stack endplates and electrical buss plates are reusable). Protective aprons, gloves, and masks may be necessary for staff who dismantle FC systems, but special ventilation is not. Disassembly is fundamentally a mechanical process separating mass dominated by plastics, paper, graphite, and no toxic materials. Staff unbolt, separate, and sort the materials, taking special care to avoid gas leaks due to the pressurization on the cell stacks. An OEM may perform this disassembly in a clean room to preserve material quality, not for occupational health reasons.
- The manufacturers aggregate metallic cell components by material type and send them back for reclamation through their supply chain. They also reclaim precious metals from the membrane-electrode-assembly through credit agreements with suppliers. They typically consider polymeric membrane materials unusable, and employees estimate a fraction (perhaps 20–40%) of the bulk materials aside from the cell stack remain reusable and send the remainder to scrap.
- Niche FC markets and system designs create high product variability, making the development of an optimized recycling process difficult. The current default is to shred the system and put all pieces in a smelter at 1000 ◦C at a waste management facility to obtain the metals and a concentrate.
- Many manufacturers are likely interested in recovering materials from any fuel cell, including ones not of their own design. Several trade precious metals for PGM materials from various sources beyond fuel cells (car catalytic converters, for example). However, this practice could raise concerns about distributing proprietary system design information. If possible, the best practice is to provide the original OEM or associated parent/subsidiary companies with the right of first refusal.

THE CURRENT STATE OF THE END-OF-LIFE VALUE CHAIN FOR FUEL CELLS AND WATER ELECTROLYZERS

Fuel Cell Manufacturers **without** Established EoL Processes [29]

EPRI previously interviewed manufacturers and material suppliers to gain insights into the current EoL processes deployed within the FC value chain. The first step was to determine fuel cell manufacturer takeback policies.

FC manufacturers without established EoL processes: Some manufacturers have no EoL processes defined; others are developing economically feasible processes that could overcome transportation and shipping costs.

Some FC manufacturers, such as PlugPower, did not provide any EoL management services as of 2021, and instead suggested that customers work with decommissioning or engineering firms for disposal despite receiving an increasing number of customer requests for EoL agreements.

The BoP consists of standard mechanical and electromechanical components that are disposable through common waste management processes. Bulk materials, such as steel components, are likely salvageable.

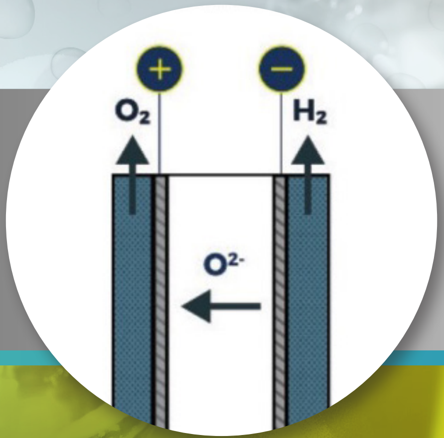
THE CURRENT STATE OF THE END-OF-LIFE VALUE CHAIN FOR FUEL CELLS AND WATER ELECTROLYZERS

How Manufacturers Determine Costs [29]

EPRI's 2021 interview with FC manufacturers found no direct information on EoL costs for FCs available. However, EPRI obtained insights into how manufacturers determined costs.

- Some manufacturers interviewed **build the cost of decommissioning into the overall system costs** at the point of project design. Doing so ensures they can recover the PGM materials directly and protect their intellectual property from third-party analysis.
  - A possible risk is that without a robust FC and WE waste management sector, a manufacturer's closure or sale to a different firm could jeopardize the EoL processes defined in customer agreements.
- Other manufacturers interviewed included EoL costs as part of their initial demonstration-scale projects, but as the company began to scale, they **shifted the onus to the customer** and required them to acquire independent EoL services.
  - Another potential risk of the rapid deployment of FC and WE in the absence of feasible commercial options or regulations is that more manufacturers may begin cutting corners on EoL processes.
- Some manufacturers interviewed **account for the expected credit generated by recovering precious or semi-precious material** when calculating the decommissioning cost. They do this by offering customers a charge credit toward a replacement stack to incentivize returning the stack to their facility. Other manufacturers use a service plan approach to address these costs.
  - The risk that customers may choose not to purchase more products from the same manufacturer would limit the incentive for a credit versus an EoL cash option.
  - The specific design of the FC is a driving factor in costs. As technology improves, the mass of high-value materials will likely decrease. This is a potential risk if other regulations and incentives are not in place beforehand, as the economic motivation to recycle stack materials will also decrease.

CONSORTIA ACTIVELY ADDRESSING END-OF-LIFE ASPECTS

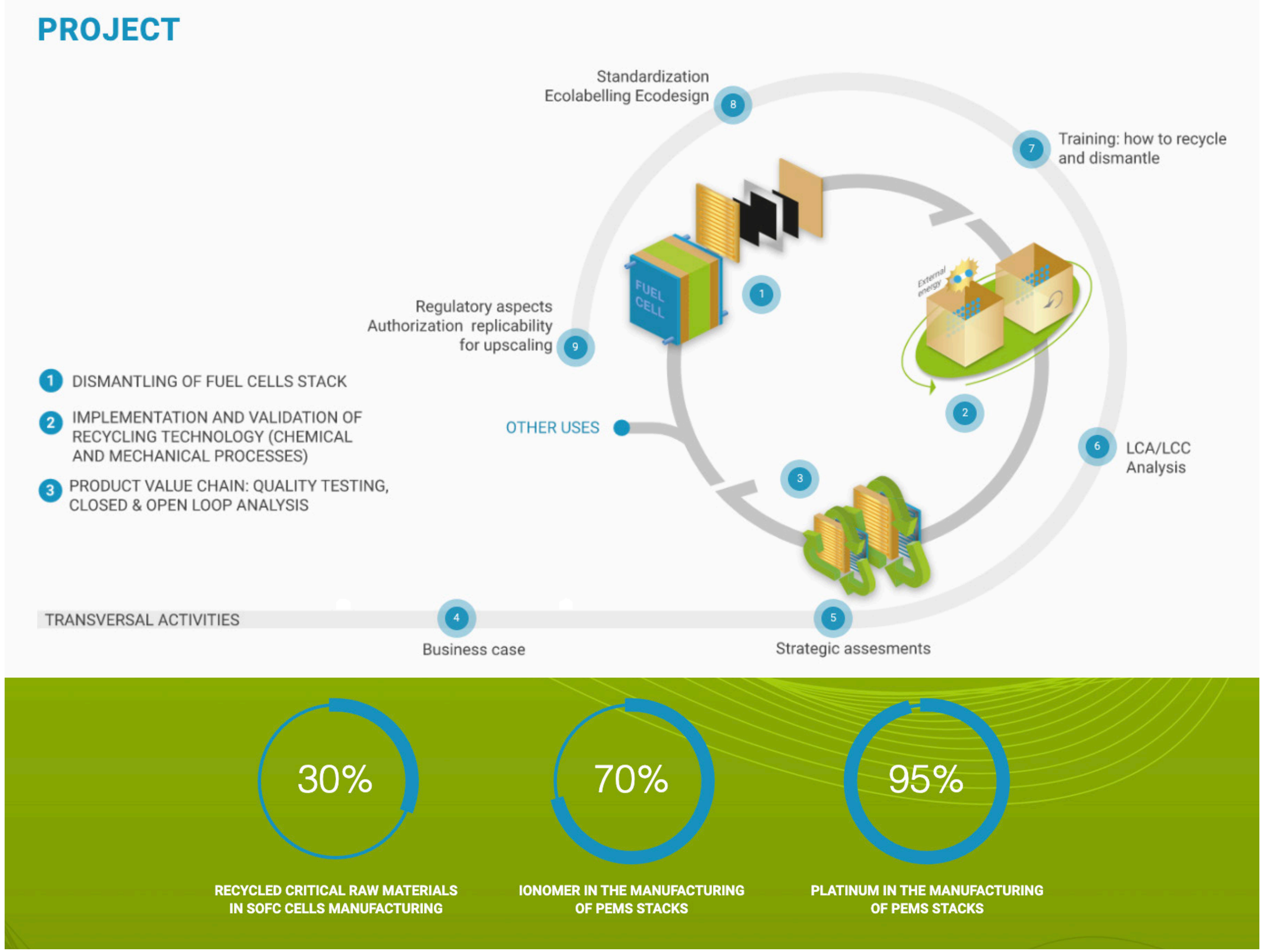


BEST4HY

The BEST4Hy program is an EU-based, international partnership developing technologies for the recovery of critical raw materials from hydrogen technologies.

The overall objective is to develop and validate recycling technologies for PEMFC and SOFC to ensure critical raw materials can be recycled into new products.

The scope includes the recovery of PGMs, rare earth elements, cobalt, and nickel.



The BEST4Hy project focus areas (top) and minimum targets for recycled material (bottom) [30]

U.S. DOE CLEAN HYDROGEN TECHNOLOGY RECYCLING

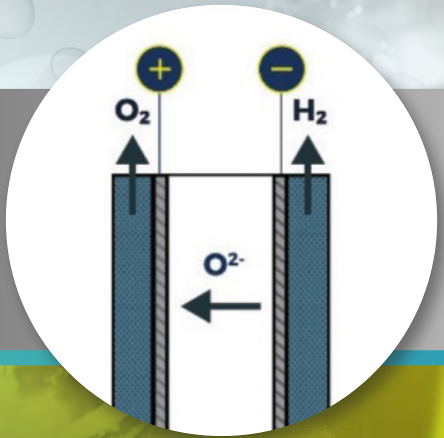
A U.S. Hydrogen and Fuel Cell Technologies Office solicitation resulting from the Bipartisan Infrastructure Law (DE-FOA-0002922 Topic 6) aims to create a large $50M multi-disciplinary recovery and recycling consortium of industry, academia, nonprofits, and national laboratories to address EOL and supply chain challenges for low-temperature PEM fuel cell and electrolyzer systems.

Proposals were due in July 2023, and the DOE expects to announce awards before the end of the year.

The initial phase activities will include the following:

- Life cycle assessment and techno-economic analysis of material recovery and recycling processes
- Research and development of PGM, ionomer/ membrane, and other stack component recovery and recycling
- Automatic disassembly
- “Design for recyclability”

ACRONYMS AND ABBREVIATIONS



ACRONYMS AND ABBREVIATIONS

Key Terms

ABBREVIATION	MEANING
EoL	end of life

Names

ABBREVIATION	MEANING
DOE	Department of Energy
EU	European Union
OECD	Organization for Economic Co-operation and Development
U.S.	United States

Technological Terms

ABBREVIATION	MEANING
BoP	balance of plant
GDL	gas diffusion layer
HTM	hydrometallurgical
MEA	membrane electrode assembly
PGM	platinum group metal
PMT	pyrometallurgical
Pt	platinum
Ni	nickel
H_2	hydrogen
H_2O	water
kg	kilogram

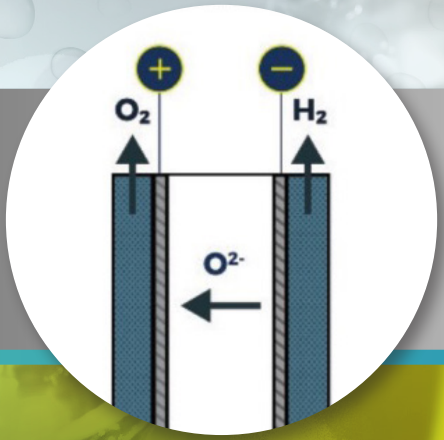
Fuel Cell Types

ABBREVIATION	MEANING
AFC	alkaline fuel cell
HTFC	high-temperature fuel cell
LTFC	low-temperature fuel cell
MCFC	molten carbonate fuel cell
PAFC	phosphoric acid fuel cell
PEMFC	polymer electrolyte membrane/proton exchange membrane fuel cell
SOFC	solid oxide fuel cell

Water Electrolyzers

ABBREVIATION	MEANING
AEMWE	anion exchange membrane water electrolysis
AWE	alkaline water electrolysis
PEMWE	polymer electrolyte membrane/proton exchange membrane water electrolysis
SOEC	solid oxide electrolysis cell

REFERENCES



REFERENCES

1. U.S. Department of the Interior. Office of the Secretary. *Final List of Critical Minerals 2018*. 83 FR 23295, Vol. 83, No. 97. Washington, D.C.: pp. 23295–23296. https://www.federalregister.gov/d/2018-10667.
2. U.S. Department of Energy. Office of Energy Efficiency & Renewable Energy. Hydrogen and Fuel Cell Technologies Office. “H2@Scale.” https://www.energy.gov/eere/fuelcells/h2scale.
3. HyTechCycling. Home page. https://hytechcycling.eu/.
4. *Executive Summary: Fuel Cell Technology Assessment—Potential Future Costs and Low-Carbon Fuel Considerations.* EPRI, Palo Alto, CA: 2023. 3002026260.
5. *Utility-Scale Low-Carbon Fuel Cells.* EPRI, Palo Alto, CA: 2020. 3002019891.
6. *Fuel Cells for Utility-Scale, Low-Carbon Power Generation Technology Update.* EPRI, Palo Alto, CA: 2021. 3002020540.
7. Encyclopaedia Britannica, Inc. *Fuel Cell: Media.* Britannica.com. https://www.britannica.com/technology/fuel-cell/images-videos.
8. E. D. Wachsman and K. T. Lee, “Lowering the Temperature of Solid Oxide Fuel Cells,” *Science.* Vol 334, No. 6058, pp. 935–939 (2011). https://www.science.org/doi/10.1126/science.1204090.
9. *Water Electrolyzer Stack Degradation.* EPRI, Palo Alto, CA: 2022. 3002025148.
10. *Executive Summary: Electrolyzer System Design Fundamentals and Durability Considerations.* EPRI, Palo Alto, CA: 2023. 3002026353.
11. *Safety Considerations in Electrolyzer Operation for Hydrogen Production.* EPRI, Palo Alto, CA: 2023. 3002027908.
12. *Insight Report on Electrolyzer Technologies.* EPRI, Palo Alto, CA: 2022. 3002021864.
13. 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.* Vol. 44, No. 38, pp. 20965–20977 (2019). https://doi.org/10.1016/j.ijhydene.2019.01.110.
14. U.S. Department of Energy. *Water Electrolyzers and Fuel Cell Supply Chain: Supply Chain Deep Dive Assessment.* Response to Executive Order 14017, “America’s Supply Chains.” Feberuary 24, 2022. https://www.energy.gov/sites/default/files/2022-02/Fuel%20Cells%20%26%20Electrolyzers%20Supply%20Chain%20Report%20-%20Final.pdf.
15. A. Lotrič, M. Sekavčnik, I. Kuštrin, and M. Mori, “Life-cycle assessment of hydrogen technologies with the focus on EU critical raw materials and end-of-life strategies,” *International Journal of Hydrogen Energy*. Vol. 46, No. 16 (2021). https://doi.org/10.1016/j.ijhydene.2020.06.190.

16. HyTechCycling EU Fuel Cells and Hydrogen Joint Undertaking, *D4.3 Case Studies with New Strategies in Dismantling and Recycling Stage*, Grant number 700190, 2019. https://hytechcycling.eu/wp-content/uploads/d4-3-case-studies-with-new-strategies-in-dismantling-and-recycling-stage.pdf.

17. S. Fiorot, "Results analysis of the questionnaires to FCH manufacturers, recycling centers, distributors and end users," presented at the HyTechCycling Dissemination Workshop, Institute IMDEA Energy, Madrid, Spain (March 2018). https://hytechcycling.eu/wp-content/uploads/06_Results-analysis-of-QS-to-manufacturers-recycling-centers.pdf.

18. U.S. Environmental Protection Agency. "PFAS Explained." EPA.gov. https://www.epa.gov/pfas/pfas-explained.

19. The Federation of German Industries (BDI) position paper, "Restriction of PFAS: Evaluation of the envisaged restriction procedure." September 2021. https://english.bdi.eu/publication/news/eu-chemicals-strategy-restriction-of-pfas.

20. Communication with staff and public information from The Chemours Company, 2023.

21. U.S. Department of Energy. *Critical Materials Assessment.* July 2023. https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf.

22. HyTechCycling EU Fuel Cells and Hydrogen Joint Undertaking, *D2.1 Assessment of Critical Materials and Components in FCH Technologies,* Grant number 700190, 2018. https://hytechcycling.eu/wp-content/uploads/d2-1-assessment-of-critical-materials-den-components-in-fch-technologies.pdf.

23. HyTechCycling EU Fuel Cells and Hydrogen Joint Undertaking, *D4.2 LCA of Materials Represented in FCH Technologies,* Grant number 700190, 2018. https://hytechcycling.eu/wp-content/uploads/d4-2-lca-of-materials-represented-in-fch-technologies.pdf.

24. S. Kiemel, T. Smolinka, F. Lehner, J. Full, A. Sauer, and R. Miehe, "Critical materials for water electrolyzers at the example of the energy transition in Germany," *International Journal of Energy Research.* Vol. 45, No. 7, pp. 9914–9935 (2021). https://doi.org/10.1002/er.6487.

25. ExplainMyStuff. Home page. https://explainmystuff.com/.

26. A. M. Ferriz, A. Bernad, M. Mori, and S. Fiorot, "End-of-life of fuel cell and hydrogen products: A state of the art," *International Journal of Hydrogen Energy.* Vol. 44, No. 25, pp. 12872–12879 (2019). https://doi.org/10.1016/j.ijhydene.2018.09.176.

27. A. Valente, D. Iribarren, and J. Dufour, "Results from 'New Recycling Technologies Applied to FCH Products'", presented at the HyTechCycling Dissemination Workshop, Institute IMDEA Energy, Madrid, Spain (March 2018). https://hytechcycling.eu/wp-content/uploads/03_Results-from-%E2%80%9C-New-recycling-technologies-applied-to-FCH-products%E2%80%9D.pdf.

28. The Scottish Government. Energy and Climate Change Directorate. *Assessment of electrolysers: report.* October 13, 2022. https://www.gov.scot/publications/assessment-electrolysers-report/.

29. *Low-Carbon Backup Generator Technology Review.* EPRI, Palo Alto, CA: 2021. 3002020505.

30. Best4Hy. Home page. https://best4hy-project.eu/.

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