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Life Cycle Fluoropolymer Management in Proton Exchange Membrane Electrolysis

Parikhit Sinha * and **Sabrine M. Cypher**

Electric Hydrogen Co., Natick, MA 01760, USA; scypher@eh2.com
* Correspondence: psinha@eh2.com

Abstract: Concerns over the life cycle impacts of fluoropolymers have led to their inclusion in broad product restriction proposals for per- and poly-fluorinated alkyl substances (PFAS), despite their non-bioavailable properties and low exposure potential in complex, durable goods such as non-consumer electrical products. Based on the hypothesis that manufacturers are most able to manage the environmental impacts of their products, practical engineering approaches to implementing life cycle fluoropolymer stewardship are evaluated to bridge the ongoing debate between precautionary and risk-based approaches to PFAS management. A life cycle thinking approach is followed that considers product design and alternatives, as well as the product life cycle stages of material sourcing, manufacturing, field deployment, and end-of-life. Over the product life cycle, the material sourcing and end-of-life stages are most impactful in minimizing potential life cycle PFAS emissions. Sourcing fluoropolymers from suppliers with fluorosurfactant emissions control and replacement minimizes the potential emissions of bio-available PFAS substances. A stack-as-service approach to electrolyzer operations ensures a takeback mechanism for the recycling of end-of-life fluoropolymer materials. Retaining electrolytic hydrogen's license to operate results in over USD 2 of environmental and health benefits per kilogram of hydrogen produced from reduced greenhouse gas and air pollutant emissions compared to conventional hydrogen production via steam methane reforming.

Keywords: renewable energy; PFAS; product stewardship; recycling

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1. Introduction

1.1. Fluoropolymers and PFAS

Fluoropolymers are a widely commercialized group of organofluorine substances, consisting of repeated fluorinated organic monomers (Table 1). They are part of a broader family of per- and poly-fluorinated alkyl substances (PFAS) that are becoming subject to increased regulation globally. Historically, such regulation has focused on non-polymer PFAS such as perfluorooctane carboxylate (PFOA) and perfluorooctane sulfonate (PFOS), which are small molecules that exhibit hazardous and bio-accumulative properties at low concentrations. The International Agency for Research on Cancer (IARC Volume 135) classifies PFOA and PFOS as carcinogenic to humans (Group 1) and possibly carcinogenic to humans (Group 2B), respectively. In contrast, fluoropolymers are large, insoluble, inert solids that are not hazardous or bio-accumulative [1,2]. However, concerns have been raised about the life cycle of fluoropolymers, specifically regarding the use of hazardous non-polymer PFAS (fluorosurfactants) during fluoropolymer production, and concerning end-of-life hazards from fluoropolymer disposal [3]. These concerns are leading to broad-based regulatory frameworks that may group the two classes (non-polymer and polymer) together under the PFAS umbrella.

In addition to focusing on non-polymer PFAS, historical regulation has also focused on dispersive uses, where PFAS comes into direct contact with consumers and/or the environment. For example, PFAS in cosmetics, cookware, and textiles has been regulated in some jurisdictions (e.g., State of California). The regulatory focus on PFAS with hazardous properties (high hazard) and dispersive applications (high exposure potential) follows a risk-based approach, where risk is the product of hazard and exposure [4]. Hazard and exposure potential are also the basis for the chemical prioritization process in the U.S. Toxic Substances Control Act (TSCA) [5].

Table 1. PFAS types and examples, with the focus of this study (ionomers) shown in bold.

Class	Subclass	Definition	Example
Non-polymer	Per-fluorinated alkyl substances	Compounds with fully fluorinated carbon atoms	Perfluorooctane carboxylate (PFOA) ($C_7F_{15}COOH$); Perfluorooctane sulfonate (PFOS) ($C_8F_{17}SO_3H$)
	Poly-fluorinated alkyl substances	Compounds with at least one fully fluorinated carbon atom	Fluorotelomer alcohol (FTOH) ($C_{10}F_{21}CH_2CH_2OH$)
Polymer	Fluoropolymers	Carbon-only polymer backbone with fluorines directly attached to carbon	Fluoroplastics (e.g.,): Polyvinylidene fluoride (PVDF) $(C_2H_2F_2)_n$
			Fluoroelastomers (e.g.,): Tetrafluoroethylene-propylene co-polymer (FEPM)
			Specialty flouroplastics (e.g.,): Perfluorinated sulfonic-acid (PFSA) ionomers
	Polymeric perfluoropolyethers	Carbon and oxygen polymer backbone with fluorines directly attached to carbon	Perfluoropolyalkylether
	Side-chain fluorinated polymers	Nonfluorinated polymer backbone, with fluorinated side chains	Fluorinated urethane polymers

Recently, a precautionary alternative to the risk-based approach has been proposed for PFAS regulation, in which the entire family of PFAS types (substances with at least 1 fully fluorinated carbon atom) and applications has been proposed for restriction and phase-out [6]. An argument for the precautionary alternative has been that targeted regulation does not address the full life cycle of hazards and exposures from PFAS materials [3]. While broad chemical family bans can reduce future PFAS emissions, they are not based on risk assessment science and so can result in adverse cost–benefit outcomes, where the cost of compliance is high and the health benefit is low.

1.2. Complex, Durable Goods and Proton Exchange Membrane (PEM) Electrolysis

Complex, durable goods are a class of products defined under the U.S. Toxic Substances Control Act (TSCA; 15 U.S. Code § 2605) as manufactured goods composed of 100 or more manufactured components, with an intended useful life of 5 or more years, where the product is typically not consumed, destroyed, or discarded after a single use. Use of fluoropolymers in a complex, durable good, such as a non-consumer electrical product, is an example of low-risk PFAS usage, given the low chemical-specific hazard in non-dispersive applications.

In addition to the low exposure potential in the use phase of complex, durable goods, the objective of this study is to show how potential exposure to PFAS can be minimized over the full product life cycle. A specific evaluation of proton exchange membrane (PEM) electrolysis is used to demonstrate life cycle management.

PEM water electrolysis (PEMWE) technology is used to produce green hydrogen (H_2) when operated with renewable electricity. H_2 is a versatile commodity that can be used as either a chemical feedstock or energy carrier for heat, power, or storage. For example, one of the most widely deployed and industrially important chemical reactions globally is the Haber–Bosch process that produces ammonia fertilizer from H_2 and N_2.

Most H_2 is produced from natural gas via steam methane reforming (SMR), resulting in byproduct CO_2 emissions. Green H_2 from renewable water electrolysis is a low-carbon fuel that can be used to decarbonize hard-to-abate industries, such as shipping, chemicals, refining, steel, and long-haul transport. The energy transition to low carbon fuels is dependent on cost and scale, with the U.S. Department of Energy (DOE) setting targets of a USD 150/kW PEM electrolyzer uninstalled system cost and a USD 1/kg green H_2 cost by 2031, compared to USD 1000/kW and >USD 3/kg, respectively, in 2022 [7].

1.3. Objectives and Problem Formulation

The reason for selecting the specific evaluation of PEMWE is that it represents a potentially adverse cost–benefit outcome of a broad PFAS chemical family ban. The evaluation is intended to show ways in which product life cycle management can achieve the same goals (PFAS health and environmental impact mitigation) as a broad PFAS ban, without the adverse technology impact.

Product-stewardship-based approaches to environmental management have been evaluated for other renewable energy technologies such as wind [8] and solar [9], but not for renewable hydrogen. In these studies, design, production, and end-of-life strategies have been shown to be effective in minimizing life cycle product environmental impacts. The underlying hypothesis is that manufacturers are most able to manage the environmental impacts of their products. Therefore, they do not have to assume only a passive role in complying with environmental regulations governing their products but can play a proactive role in minimizing the environmental impacts of their products.

Prior research has focused on precautionary approaches to fluoropolymer management that advocate for broad product bans to minimize PFAS emissions [3], and risk-based approaches that focus on managing PFAS substances and applications with high hazard and exposure potential, respectively [1,2]. The objective of this study is to bridge this ongoing debate between precautionary and risk-based approaches to PFAS management with practical engineering approaches to implementing stewardship over the product life cycle and to identify which actions are most impactful in minimizing potential emissions.

2. Materials and Methods

Methods follow the “life cycle thinking” approach in the U.S. National Academies framework for alternatives assessment [10]. It includes consideration of product design and alternatives, as well as the product life cycle stages of material sourcing, manufacturing, field deployment, and end-of-life. Best practices in life cycle fluoropolymer management are identified based on principles of sustainable procurement, resource efficiency, and circular strategies. Sustainable procurement promotes minimization of environmental impact in raw material production, resource efficiency minimizes the material intensity of manufacturing, and circular strategies promote recycling and the use of recycled content. Material intensity refers to the quantity of materials per unit of production (e.g., kilograms of fluoropolymer usage per megawatt of electrolyzer capacity), which is a function of system power density.

Life cycle product stewardship falls under the broader concept of extended producer responsibility, where manufacturers expand the scope of responsibility for their environmental impacts. Instead of confining responsibility to within their manufacturing operations and product use, responsibility is expanded to include upstream sourcing of raw materials and downstream management of product end-of-life (cradle-to-grave).

In addition to life cycle management, the life cycle environmental and health benefits of electrolytic hydrogen production are compared to conventional hydrogen production with steam methane forming. The comparison helps quantify the benefits of retaining electrolytic hydrogen’s license to operate. Life cycle benefits follow the approach of Wiser et al. [11] used for evaluating the environmental and public health benefits of solar energy in the U.S. These methods use environmental damage factors (USD per kg of pollutant) for air pollutants and greenhouse gases from the U.S. Environmental Protection Agency (EPA).

The environmental damage factors for air pollutants (NO_x, $PM_{2.5}$, SO_2) are from the U.S. EPA regulatory impact analysis for the California region [12], adjusted from 2011 to 2020 dollars using a 3% discount rate. The damage factors for greenhouse gases (CO_2, CH_4, N_2O) are from the U.S. EPA regulatory impact analysis in 2020 dollars for emission year 2020 [13]. The damage factor for a given pollutant is multiplied by its life cycle emissions (kg pollutant per kg H_2 production) to yield the environmental cost (USD per kg H_2 production).

While the environmental damage factors are obtained from U.S. EPA, the life cycle emissions are obtained from the Argonne National Laboratory GREET model. Life cycle emissions for SMR are from Argonne National Laboratory's R&D GREET1_2023 model and impacts for PEMWE are from the R&D GREET2_2023 model [14]. Both R&D GREET models utilize the Excel platform, and life cycle environmental and health benefits are also estimated in Excel.

For SMR, a 480-ton-per-day plant with steam export is modeled, along with the fuel cycle of natural gas (extraction, processing, compression, and transportation). For PEMWE, a 998 kW plant with 97% capacity factor is modeled with 7 year lifetime for the cell stack and 20 year balance of plant lifetime, assuming 55.5 kWh of renewable electricity per kg of H_2 production.

For additional comparison, life cycle emissions for alkaline electrolysis are also obtained from the R&D GREET2_2023 model [14]. For alkaline electrolysis, a 3836 kW plant with a 90% capacity factor is modeled with 10 year lifetime for the cell stack and 20 year balance of plant lifetime, assuming 51.8 kWh of renewable electricity per kg of H_2 production. For all three technologies (SMR, PEMWE, and alkaline electrolysis), default model parameters are used in the GREET model, representing the typical scale and duration of commercial operations. Results are analyzed per kg of H_2 production for comparability.

3. Results and Discussion

The results of the "life cycle thinking" approach to fluoropolymer management in PEMWE are summarized below. Best practices are identified across the life cycle stages of product design and alternatives assessment, material sourcing, manufacturing, field deployment, and end-of-life (Figure 1), and discussed in turn.

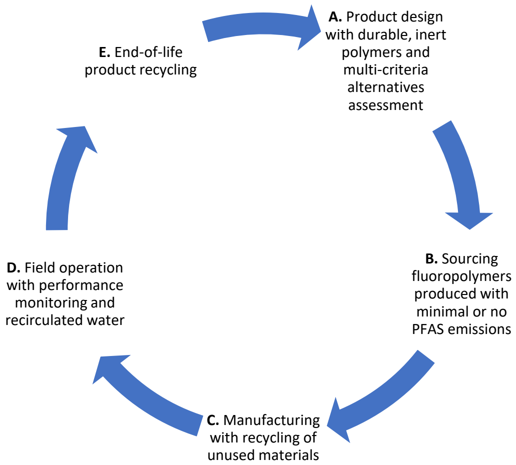

Figure 1. Life cycle stewardship approach to PFAS management in PEMWE.

3.1. Product Design

At the core of the PEMWE technology is the electrolyzer cell (Figure 2), which consists of an anode where water is split to produce O_2 and protons (H^+), and a cathode where protons combine with electrons to produce H_2 gas. The PEM at the center of the cell acts as a channel for protons and insulator against electrons and gases (O_2).

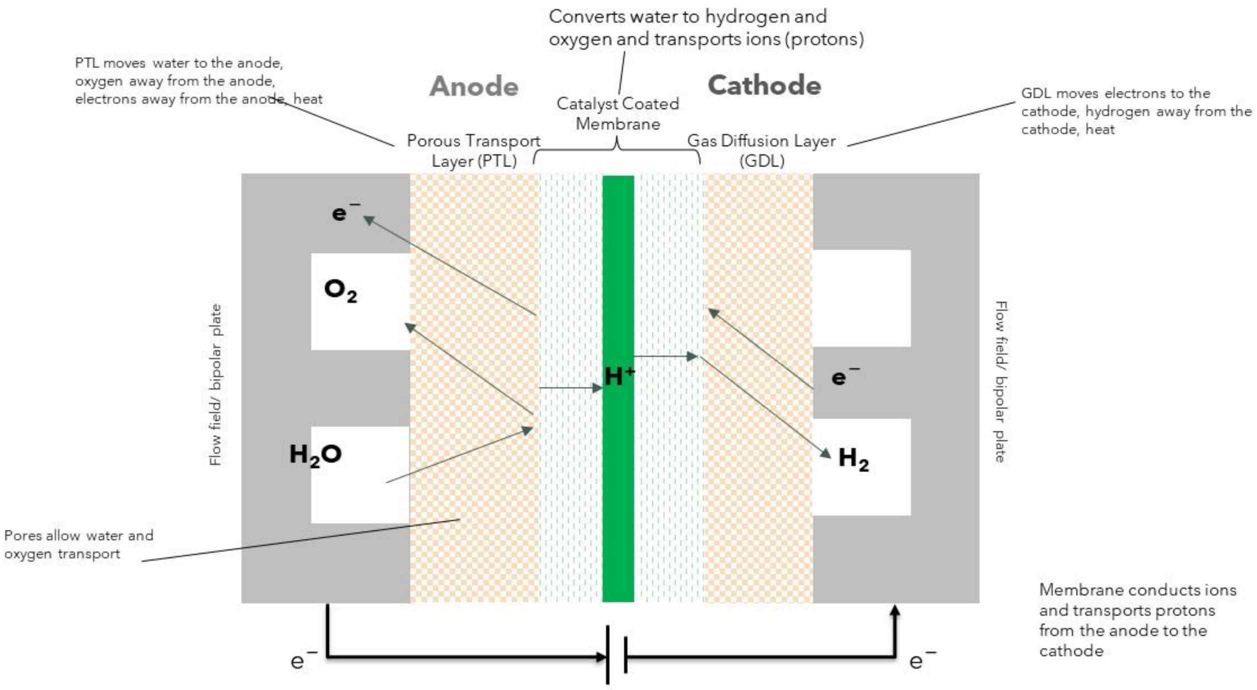

Figure 2. Cross-section of PEM electrolyzer cell.

The specific membrane materials used in PEMWE are fluoropolymers of perfluorinated sulfonic acid (PFSA ionomers), which are fluoropolymers with pendant sulfonic acid groups. The fluoropolymer backbone is hydrophobic, while the negatively charged ionic side chains are conductive for positively charged ions (H^+; protons). The membranes are cast as thin, solid sheets, that are typically <100 µm in thickness. In order to function in water electrolysis, the membrane needs to be insoluble in water and selectively conductive while durable in harsh operating conditions (Table 2).

Table 2. PEM electrolyzer stack operating conditions [15,16].

Property	Value
Temperature	Up to 90 °C
Pressure	Up to 30 bar
pH	Acidic
Redox conditions	Oxidizing
Operating hours	40,000–80,000

As shown in Table 1, PFSA ionomers are part of the fluoropolymer family [2]. Some chemical, physical, and toxicological properties of PFSA ionomers are summarized in Table 3. In addition to their use in electrolysis, PFSA ionomers in ion exchange membranes have been identified as the best available technology for one of the chemical industry's fundamental chemical processes, chlor-alkali production, which produces chlorine and sodium/potassium hydroxide through the electrolysis of brine. The use of ion exchange membranes is a safer alternative compared to historic chlor-alkali production with asbestos diaphragm cells or mercury electrode cells [17].

Fluoropolymer material usage in PEM electrolyzer stacks is ~14 metric tons per GW capacity (Figure 3). For perspective, the DOE Hydrogen Program Record (Record 24001) indicates total installed capacity of PEM electrolyzers in the U.S. of ~0.1 GW in 2024, with an additional ~0.7 GW under construction and a planned future firm capacity of ~3.8 GW. Fluoropolymer usage per GW in PEM electrolyzer stacks is 1–3 orders of magnitude lower than the annual fluoropolymer use in the other main downstream use categories in Europe (Figure 3). Design strategies for reducing fluoropolymer usage include increased electrolyzer system power density, which reduces fluoropolymer usage per unit of system capacity and per kg of H_2 production. Increased power density means that fewer stacks are needed to achieve the rated electrolyzer system capacity, thereby reducing fluoropolymer and other material demand.

Table 3. PFSA ionomer properties [2].

Property	Value
Molecular weight	>100,000 g/mol
Solubility	Insoluble in water
Operating temperature	Maximum operating temperature of 220–240 °C
Bioavailability	Not bioavailable or bioaccumulative—cannot be absorbed through cell membrane and does not interact with cell surface

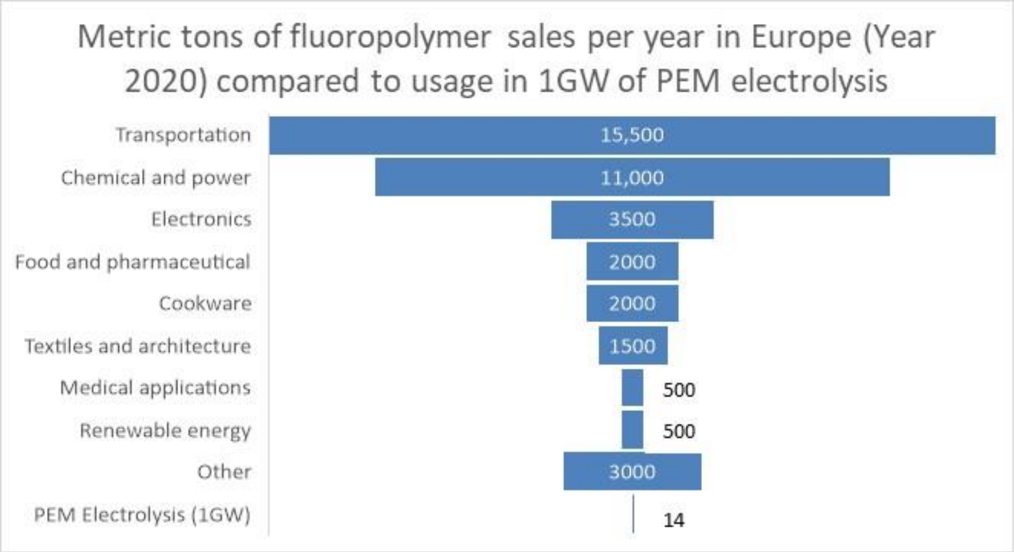

Figure 3. Annual fluoropolymer sales to European downstream product categories [18] compared to usage in PEMWE (1GW) [19].

3.2. Alternatives

Research on replacing conventional perfluorinated ionomers with fluorine-free materials has been conducted for decades, but commercialization has been limited by degradation related to poor oxidation stability in industrial operating conditions [20]. Example alternative PEMWE materials include hydrocarbon membranes, polysulfone, sulphonated polyetheretherketone (SPEEK), and electrospun polybenzimidazole-type materials. Due to the lack of durability from oxidation by oxygen radicals, the technical suitability of these alternatives is, at present, unclear, and the alternatives are not yet available for large-scale application [21]. Durability has both technical and environmental benefits, since durable materials require fewer replacements over the system life. Overall, factors such as safety, availability, performance, cost, and life cycle environmental and social impacts factor into alternatives assessment [10]. As part of sustainable design practices, alternatives should be revisited when substitute materials show potential for achieving performance comparable to incumbent materials, factoring in the above ~decade-long timeline required to introduce new materials at commercial scale.

With regards to competing electrolysis technologies, alkaline electrolysis operates by transporting hydroxide ions (OH^-) through an alkaline liquid electrolyte (sodium or potassium hydroxide) from the cathode to the anode, with hydrogen being generated at the cathode. Compared to PEMWE, alkaline electrolysis yields a lower-purity product due to higher gas crossover rate; it is not suitable for intermittent power sources like renewables due to a narrow acceptable current density range, and it uses corrosive chemicals during operation [15]. Alkaline electrolysis is currently dependent on fluoropolymer use for production of the alkaline liquid electrolyte. Specifically, sodium hydroxide and potassium hydroxide are manufactured with the chlor-alkali production process which uses fluoropolymer-containing materials in membranes, gaskets, gas-diffusion electrodes, and other construction materials [2].

Newer approaches to alkaline electrolysis use solid alkaline exchange membranes (AEM) as the electrolyte but have had lower energy efficiencies and poor durability due to chemical instability [2]. Steam reforming of natural gas emits significant amounts of greenhouse gases in conventional hydrogen production. Overall, these alternative technologies differ in their flexibility, performance, and product quality characteristics compared to PEM water electrolyzers.

3.3. Material Sourcing

The PFSA ionomer used in the PEM membrane is produced using emulsion polymerization, with fluorosurfactants used as a processing aid. The fluorosurfactants are non-polymer PFAS (Table 1), which pose a higher hazard than the fluoropolymers being produced. In response to concerns over fluorosurfactant hazards, major fluoropolymer producers have collectively committed to achieving low emissions of these substances. Table 4 shows the commitment levels and target dates for emissions to air and water. Emissions controls used to achieve these levels include thermal oxidation for air emissions and several approaches for water emissions, including activated carbon, reverse osmosis, ion exchange, and nano-filtration.

Table 4. Emissions control commitments (average emission factors) for non-polymeric processing aid PFAS residues in fluoropolymer manufacturing. Average emission factors are calculated as annual emission of added or generated non-polymeric processing aid PFAS residues/total annual amount of fluoropolymers produced on site [22].

Target Year	Average Emissions to Air	Average Emissions to Water
End 2024	0.009%	0.001%
End 2030	0.003%	0.0006%

In addition to emissions controls, some fluoropolymer producers have committed to phasing out fluorosurfactant use as processing aids in fluoropolymer production [23]. In general, for downstream users, fluorosurfactant emissions control and replacement are sustainable procurement criteria for life cycle fluoropolymer management. Downstream users can facilitate innovation in the supply chain with a collaborative approach that involves testing early engineering samples and providing some flexibility in specifications to de-risk new fluoropolymer production processes.

3.4. Product Manufacturing

The core assembly of a PEMWE cell is the catalyst-coated membrane (CCM) (Figure 2). The CCM is composed of catalyst/fluoropolymer composite film layered with fluoropolymer membranes. The catalyst layers are usually cast from polymer dispersions blended with catalysts, while the membranes can be extruded or cast from fluoropolymer dispersion. Over 90% of input fluoropolymer and catalyst materials are incorporated into products. The remaining materials are reclaimed and reused through captive reclamation hydrometallurgical recycling methods [24]. These methods can be used to recover catalysts from electrolyzer membrane systems, allowing for the separate recovery of critical minerals and fluoropolymers from the electrolyzer, and return to the initial manufacturing process (Figure 4). In addition, water used for testing the electrolyzer is purified with reverse osmosis, recirculated in the cell stack, and consumed during operation to produce H_2 and O_2.

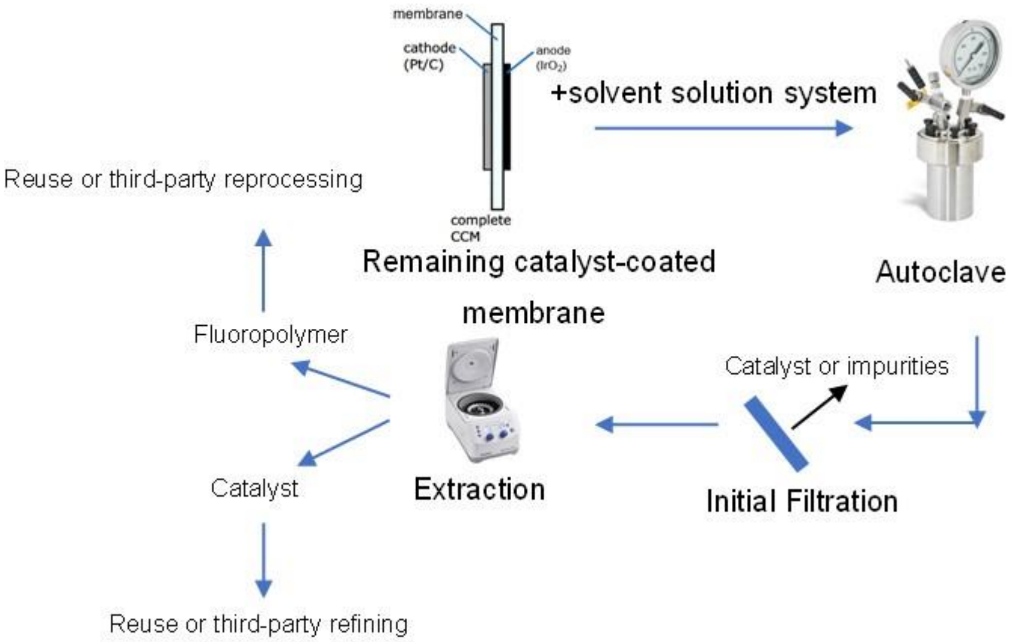

Figure 4. Schematic process flow for fluoropolymer and catalyst separation from catalyst-coated membranes in PEM electrolyzer cells.

A key step in enabling recovery of unused materials is the material flow mapping of the inputs, outputs, and byproduct streams in manufacturing by a process tool. The mapping process facilitates proper segregation of byproducts by material type for subsequent reclamation. In the case of reclaiming unused catalyst-coated membranes (CCM; Figure 4), effective separation of fluoropolymers from catalyst metals is necessary to maximize reuse potential for both materials.

3.5. Field Deployment

Electrolyzers split water to produce H_2 and O_2 gas as their only reaction products. Electrolyzer stacks are designed for 40,000+ h of operation (Table 2), during which water is purified, recirculated within the electrolyzer, and consumed to produce H_2 and O_2 (Figure 5). Wastewater is generated upstream of the electrolyzer stack operation in the form of reject water from the reverse osmosis/deionizer (RODI). Water is consumed at a stoichiometric rate of 9 L per kg H_2, with water molecules recirculated numerous times in the enclosed loop before being converted to H_2 and O_2. The reverse osmosis/deionizer runs intermittently to make up water consumed in the electrolysis process. Operating conditions (e.g., voltage, current density, temperature) are continuously measured at individual cell and/or stack level to monitor performance and degradation.

In the case of fluoropolymer management, water recirculation ensures closed-loop operation, minimizing both water consumption and wastewater generation. In Figure 5, flows of water are indicated in blue, showing output from the RODI water purification system, input into the electrolyzer stack, and water recirculation. Water efficiency can be measured in comparison to the above stoichiometric consumption rate, with differences primarily due to losses from water purification and water vapor lost with O_2 release.

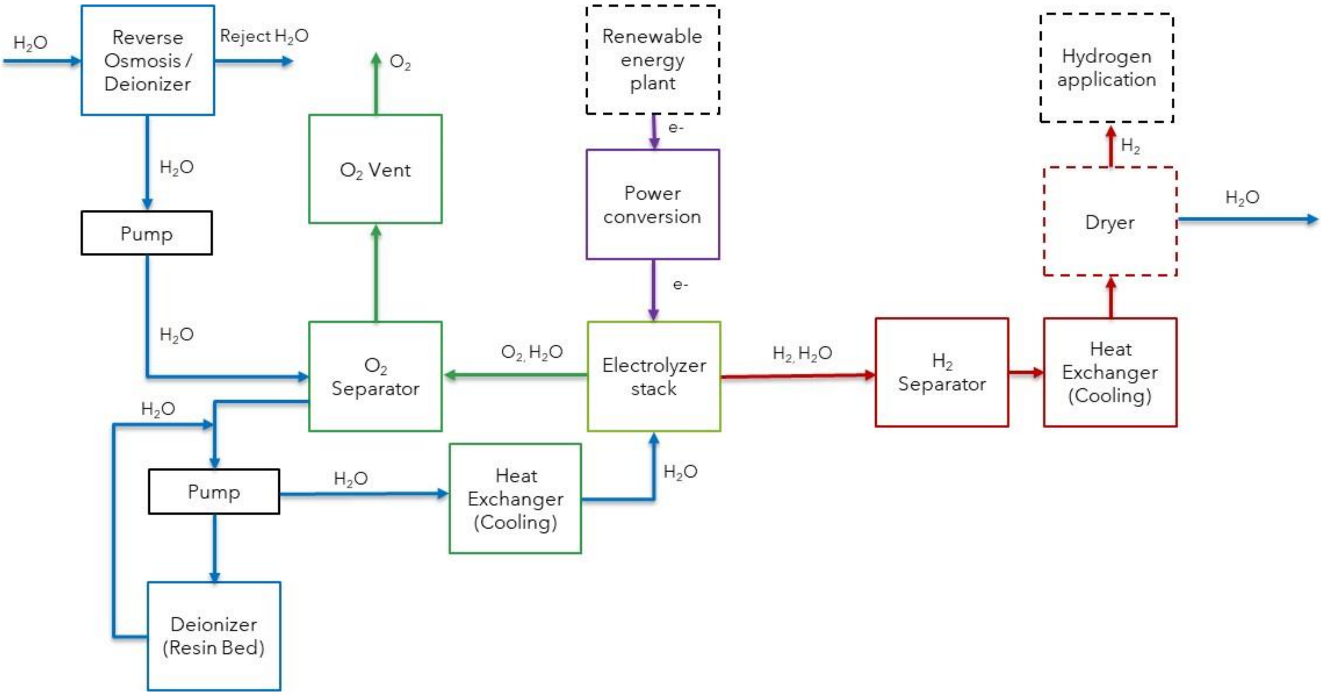

Figure 5. Schematic process flow of electrolyzer plant operation, with flows of water, electricity, hydrogen, and oxygen shown in blue, purple, red, and green, respectively.

3.6. End-of-Life

Hydrometallurgical recycling methods used to reclaim materials during manufacturing can also be used for critical mineral and fluoropolymer recovery from end-of-life electrolyzer stacks. The presence of high-value components in the stack's cells (Table 5) provides a strong economic incentive for takeback over disposal. End-of-life fluoropolymers can be recycled or reused (Figure 4). A closed-loop system for metal and fluoropolymer recovery from electrolyzers is being developed under the H2CIRC consortium funded by the U.S. Department of Energy [25].

Table 5. Quantities of high-value components in PEM electrolyzer stacks [19].

Cell Stack Component	Target Material Recycled	Quantity (kg/MW)
Membrane–electrode assembly	Fluoropolymer	14
	Iridium	0.6
	Platinum	0.4
	Titanium	57
Bipolar plate	Titanium	108

The cell stacks within an electrolyzer plant can be viewed partly as a product and partly as a service. Because the stack lifetime (Table 2) is less than the plant lifetime (~20 yrs), the plant owner/operator needs to develop a stack maintenance schedule prior to commissioning the plant. Under this schedule, the stack equipment producer provides availability for stack replacement to ensure operating performance within specifications. Under such an arrangement, when stacks need refurbishment or replacement at the end of their expected lifetime, they are exchanged with the stack manufacturer during installation of the new stack. This stack-as-service approach ensures a takeback mechanism for end-of-life fluoropolymers and other stack materials.

3.7. Life Cycle Benefits

The advantage of life cycle product stewardship compared to precautionary product restrictions is to minimize environmental impacts from fluoropolymer usage, while preserving license to operate. The latter maintains the life cycle benefits of renewable electrolysis over conventional H_2 production with natural gas SMR. As shown in Figure 6, PEM renewable electrolysis has lower life cycle impacts by 1 to 2 orders of magnitude for environmental categories of air pollution, carbon and water footprint, and energy use.

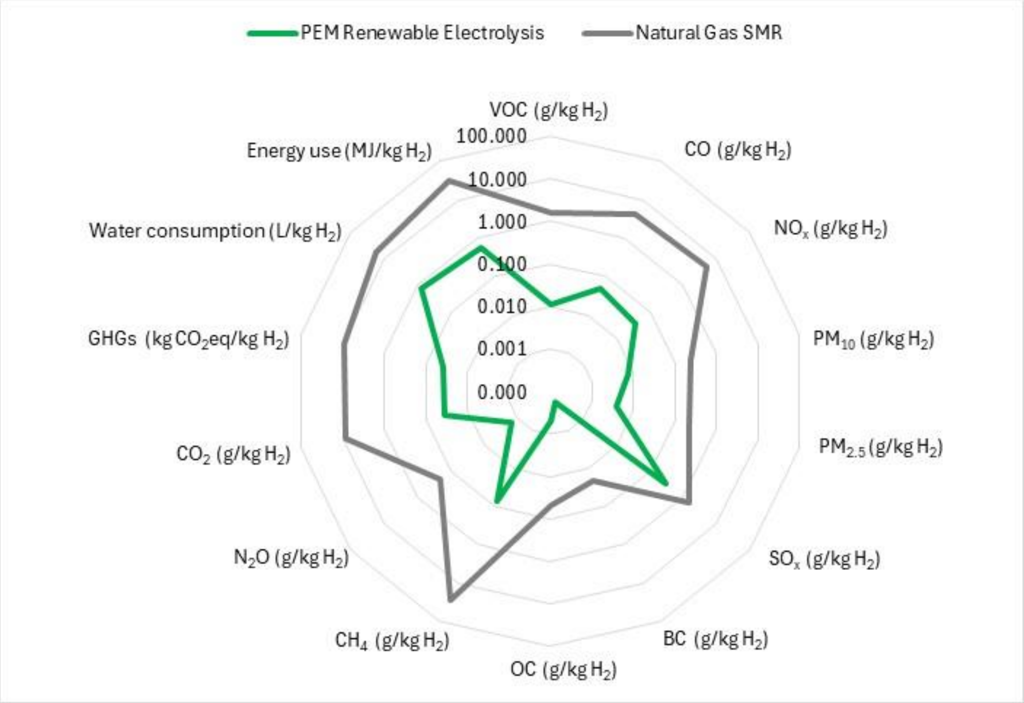

Figure 6. Life cycle impacts of hydrogen production from PEMWE with renewable electricity and steam methane reforming via natural gas for air pollution, greenhouse gas, water, and energy environmental impact categories [14]. Abbreviations: VOC—volatile organic carbon; PM—particular matter; BC—black carbon; OC—organic carbon; GHGs—greenhouse gases.

As shown in Table 6, renewable PEMWE also has 2–3 times lower life cycle environmental impacts compared to renewable alkaline electrolysis. The difference is because alkaline systems are more material-intensive, with stack and balance of plant weights of 23 and 40 metric tons per MW, respectively, compared to 0.7 and 19 metric tons per MW, respectively, for PEMWE [19].

In addition to life cycle environmental impacts, the environmental costs associated with those impacts can be estimated using environmental damage factors. For example, in the case of NO_x emissions, the life cycle impact for natural gas SMR (4.930 g NO_x/kg H_2) can be multiplied by the environmental damage factor for NO_x (USD 31,633/metric ton NO_x or USD 0.0316/g NO_x) to estimate the environmental cost of NO_x emissions. When the same is undertaken for NO_x emissions from PEMWE and subtracted from the result for SMR, the environmental benefit of replacing SMR with PEMWE is USD 0.15/kg H_2, as shown in Table 6. Overall, there are over USD 2/kg in environmental benefits from switching from conventional SMR to renewable PEMWE, mostly related to greenhouse gas (CO_2, CH_4, N_2O) emissions avoidance (Table 6).

The main factor contributing to the life cycle environmental benefits of PEMWE is USD 1.62/kg H_2 in benefits from avoided CO_2 emissions. These are based on an environmental damage factor of USD 190 per metric ton CO_2 from U.S. EPA [13], which reflects the benefit to society of reducing CO_2 emissions by a metric ton with regards to the physical, ecological, and economic impacts of climate change. Carbon pricing in the form of a carbon tax or cap-and-trade program would be needed to monetize these benefits. In the European Union (EU), a carbon border adjustment mechanism (CBAM) has been adopted for assessing and taxing the excess carbon intensity of H_2 imported into the EU, relative to the domestic EU baseline carbon intensity [26].

Table 6. Life cycle impacts and environmental costs of hydrogen production from PEM and alkaline electrolysis with renewable electricity and steam methane reforming via natural gas for air pollution, greenhouse gas, water, and energy environmental impact categories.

	Life Cycle Impacts of PEM Renewable Electrolysis [14]	**Life Cycle Impacts of Alkaline Renewable Electrolysis [14]**	**Life Cycle Impacts of Natural Gas SMR [14]**	**Environmental Damage Factor (2020 Dollars/Metric Ton) [12,13]**	**Environmental and Health Benefit of Replacing SMR with PEMWE (2020 Dollars/kg H_2)**
VOC (g/kg H_2)	0.011	0.030	1.582		
CO (g/kg H_2)	0.051	0.152	4.114		
NOx (g/kg H_2)	0.035	0.068	4.930	USD 31,633	USD 0.15
PM_{10} (g/kg H_2)	0.007	0.017	0.240		
$PM_{2.5}$ (g/kg H_2)	0.004	0.009	0.229	USD 532,008	USD 0.12
SOx (g/kg H_2)	0.288	1.231	1.482	USD 136,597	USD 0.16
BC (g/kg H_2)	0.0002	0.0004	0.021		
OC (g/kg H_2)	0.001	0.001	0.050		
CH_4 (g/kg H_2)	0.075	0.154	27.350	USD 1900	USD 0.05
N_2O (g/kg H_2)	0.002	0.003	0.198	USD 55,000	USD 0.01
CO_2 (kg/kg H_2)	0.035	0.063	8.581	USD 190	USD 1.62
GHGs (kg CO_2eq/kg H_2)	0.038	0.069	9.461		
Water consumption (L/kg H_2)	0.755	0.860	17.962		
Energy use (MJ/kg H_2)	0.544	0.989	30.997		
Total					USD 2.12

In addition to air pollution and climate impacts, multi-criteria life cycle assessment indicates factor of ~3 reduction in human toxicity impacts from PEMWE relative to natural gas SMR per kg of H_2 produced. Specifically, advanced PEMWE can reduce life cycle non-cancer and cancer human toxicity impacts by ~5 × 10^{-8} and ~1 × 10^{-8} comparative toxic units for humans (CTU_h) per kg H_2, respectively, compared to natural gas SMR [27]. CTU_h represents the estimated increase in morbidity (adverse health cases) in the population per unit mass of chemical. In California, natural gas SMR facilities have a combined production capacity of approximately 840,000 metric tons H_2 per year as of 1 January 2024 [28]. Given this production capacity, replacement of California SMR facilities with advanced renewable PEMWE facilities would correspond to ~1000 avoided adverse health cases over a 20-year plant operating period (16.8 billion kg H_2 over 20 years • ~6 × 10^{-8} CTU_h per kg H_2). While these quantitative health estimates are approximate due to uncertainty in modeling life cycle human toxicity, SMR facilities and PEMWE facilities have important differences in local air quality impacts, with the former being a local source of criteria air pollutants and the latter having zero emissions of criteria air pollutants.

4. Conclusions

Because not all PFAS substances are bioavailable and not all PFAS uses are dispersive, broad PFAS product restrictions can have technology impacts that are disproportionate to risk, as exemplified by fluoropolymer use in complex, durable goods such as PEM electrolyzers. As a best practice, concerns over the fluoropolymer life cycle should be addressed by life cycle product stewardship that minimizes non-polymer PFAS emissions during fluoropolymer production, uses enclosed systems in product manufacturing and use, and establishes circular strategies for manufacturing and end-of-life fluoropolymer materials. Life cycle management can minimize environmental impacts of fluoropolymer materials, while maintaining the considerable environmental benefits (>USD 2/kg H_2 from reduced greenhouse gas and air pollutant emissions) of renewable electrolysis over conventional H_2 production with steam methane reforming. Life cycle management also represents specific engineering strategies for working collaboratively with the supply chain and policymakers on PFAS stewardship. Out of the various life cycle product stewardship strategies, the material sourcing and end-of-life stages are most impactful in minimizing life cycle PFAS emissions. Sourcing fluoropolymers from suppliers with fluorosurfactant emissions control and replacement minimizes potential emissions of bio-available PFAS substances. A stack-as-service approach to electrolyzer operations ensures a takeback mechanism for recycling of end-of-life fluoropolymer materials.

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