Socio-Economic Analysis of a potential REACH Restriction on Fluoropolymers Nafion™ Ion Exchange Membranes

Final Report

prepared for

APM division of Chemours

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RPA
Risk & Policy Analysts

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Nafion™ Ion Exchange Membranes

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Author(s)	Julianne Oakley Charles James Robert White
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Executive Summary

Scope and methodology

An EU REACH Annex XV Restriction Proposal is being prepared for Per- and polyfluoroalkyl substances (PFAS). Risk&Policy Analysts Ltd, UK (RPA) have been engaged by Chemours Advanced Performance Materials (APM) division to undertake a study on the Socio-Economic Analysis (SEA) of the Restriction and Analysis of Alternatives (AoA) of Nafion™ ion exchange membranes (IXM, CAS 31175-20-9, EC 680-985-7). The purpose of this study is to provide APM with information to understand the impacts and unintended consequences of the proposed Restriction under a continued use versus non-use scenario. The non-use scenario is envisaged as a complete ban of PFAS from 2025 (a restriction on formulation concentrations would result in a *de facto* ban), which is assumed to be in full effect from 2026 accounting for a grace period to scale down production and sell remaining stocks. The assessment period is ten years (2026-2035), a theoretical timeframe for alternatives to be developed. To obtain data for the study, RPA carried out a systematic literature review (with valuable input from Chemours APM) and developed a survey which consisted of a questionnaire sent to a targeted list of stakeholders and follow-up telephone meetings between selected stakeholders and RPA.

Nafion and assessed sector

Currently, Nafion™ membranes are articles produced in the USA and imported into the EU. They consist of fluoropolymers that are composed of a PTFE (polytetrafluoroethylene) backbone with a perfluoroalkylether side chain ending in sulfonic acid groups. They are inert, highly stable and insoluble fluoropolymer. Nafion™ membranes and dispersions meet the persistent criteria, as most polymers do, but they are not bioaccumulative or toxic, and it does not classified for any GHS endpoints. The membranes are used in a variety of applications, but the ones that will be the focus of this report are within the domain of the hydrogen economy, i.e. the generation of energy through hydrogen as commercial fuel. This study focuses particularly on IXM membranes used in low temperature polymer electrolyte membrane fuel cells (PEMFCs, electrochemical cells which convert chemical energy from a hydrogen gas into electrical energy); and polymer electrolyte membrane water electrolysers (PEMWEs, a cell in which electrical energy is used to split water to generate high purity hydrogen).

The hydrogen economy consists of two supply chains: green hydrogen production and fuel cell manufacturing supply chains. Across these, three markets have been identified: the membrane electrode assembly (MEA) manufacturing market, the water electrolysis equipment market, and the hydrogen fuel cell market.

Alternatives

The analysis of alternatives did not identify any materials which are suitable alternatives to Nafion™ used as proton exchange membranes, largely due to the unique mechanical and chemical stability delivered by Nafion™. Hydrocarbon membranes, phenylene-based hydrocarbon membranes, are the most well-developed alternative material, however from consultation with the hydrogen economy supply chain, it was understood that hydrocarbon membranes do not have sufficient mechanical or chemical stability to be viable for use in fuel cells or electrolysers. A range of alternative fuel cell and water electrolyser technologies do not make use of fluoropolymer membranes. For fuel cells, these included alkaline fuel cells, solid oxide fuel cells (SOFCs), phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs) and high temperature polymer electrolyte membrane fuel cells (HT-PEMFCs). It was determined that these alternative fuel cell technologies are too large and heavy to replace fuel cells within the transport industry which use Nafion™ as the membrane material. HT-PEMFCs are beginning to see applications in the transport industry, however this technology is in its infancy and will not be commercially viable during the assessment period of this report. For water electrolysis, the alternative technologies considered were alkaline water electrolysers (AWEs) and anion electrolyte membrane electrolysers (AEMs). AWEs currently hold the highest share of the water electrolysis market, however the equipment is too large to supply the future demand for hydrogen, particularly in metropolitan areas. AEMs have potential to replace water electrolysers which use Nafion™, however this technology will likely not be available until after the assessment period of this report.

Chemours impact

Overall, the total profits from the continued use Nafion™ IXM have been predicted at between €976 million and €1.4 billion, with the total losses over the same assessment period estimated also at the same value. However, under a non-use scenario, the biggest impact will be on the delivery of EU policies related to the Green Deal and hydrogen economy due to a lack of suitable alternatives to Nafion™. Nafion™ materials are critical to the hydrogen economy. The availability and use of Nafion™ has allowed the development of lighter weight, low maintenance, robust fuel cell and water electrolyser technologies. As a result of these developments, the EU has been able to set out ambitious hydrogen use and production strategies.

Under a non-use scenario all the markets within scope of this SEA would be lost from the European economy due to a lack of currently viable alternatives for these markets to switch to. The economic impact of this would be the loss of between €411 and €797 million in profits from Chemours APM, over €230 million in profit lost from MEA manufacturers and over €334 million in lost profits from fuel cell manufacturers. The total losses experienced across Europe will be much higher than this once profits from water electrolysis manufacturers are accounted for.

Chemours currently employs 629 Full Time Equivalent (FTE) individuals in Europe in relation to their fluoropolymer activities. Under a non-use scenario all workers would lose their job with a social cost to Europe between €111 and €145 million. Additional unemployment will be felt throughout the hydrogen economy supply chains, but it was not possible to quantify.

At present Chemours APM have a diverse range of projects in their research and development portfolio across several sites within Europe. APM over the assessment will spend nearly €91 million on PFAS alternative R&D, while also spending an additional €190 million on operational R&D to develop and improve their manufacturing processes and logistics chains. Under a non-use scenario, APM would be forced to move its R&D outside of Europe.

Impact in the EU

The EU Hydrogen Strategy and the European Clean Hydrogen Alliance, adopted in July 2020, were developed to establish objectives to facilitate investments in clean hydrogen. Clean hydrogen produced by water electrolysis and hydrogen fuel cells are examples of capturing energy from renewable energy sources with zero-emissions of greenhouse gases (GHG). With these recent initiatives in mind, the EU values renewable hydrogen as a key aspect of achieving the Green Deal and ending reliance on fossil fuel imports from non-EU countries (REPowerEU initiative). The EU strategic goals relating to the production and consumption of renewable hydrogen set out in the Green Deal, the Clean Hydrogen Partnership are ambitious, but achievable. These goals are made possible by the progression of technology over recent years. This advancement in hydrogen production and consumption technology relies heavily on the use of fluoropolymer membranes such as Nafion™, without which the necessary Key Performance Indicators would not be met. The Hydrogen Roadmap Europe prepared by the Clean Hydrogen Partnership predicts that by 2050 1.7 million heavy-duty vehicles containing hydrogen fuel cells will be required on European roads to reach targets set under the Paris agreement. These strategies set out ambitious, short-term goals to drastically increase hydrogen production, infrastructure and aim to reduce CO_2 emissions and eliminate the EU's dependence on Russian oil and gas by 2027. The framework for the hydrogen strategies is underpinned by recent advances in water electrolysis and fuel cell technology which would not be possible without Nafion™. If a restriction on the manufacture and use of PFAS substances were to prevent Nafion™ membranes and dispersions being used in the EU, the production of electrolytic low-carbon hydrogen would be limited to the outdated and low-capacity technologies, making the strategic goals difficult if not impossible to achieve.

Table of Contents

Glossary

Acronym	Full name
AEM	Anion exchange membranes
AFC	Alkaline fuel cell
AoA	Analysis of alternatives
APM	Advanced performance materials
AWE	Alkaline water electrolysers
BoP	Balance of plant
CAGR	Compound annual growth rate
CCM	Catalyst coated membrane
CRC	Corporate Responsibility Commitment
CO	Carbon Monoxide
COF_2	Carbonyl Fluoride
DoE	Department of energy
EBA	European battery alliance
EU	European Union
EV	Electric vehicle
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
FCV	Fuel cell vehicle
FGEW	Functional group equivalent weight
FPG	Fluoropolymers product group
GHG	Greenhouse gases
HDPE	High density polyethylene
HDV	Heavy-duty vehicles
HF	Hydrogen Fluoride
HFP	Hexafluoropropylene
HT-PEMFC	High temperature polymer electrolyte membrane fuel cells
ICE	Internal combustion engine
IEM	Ion exchange membranes
IXM	Ion exchange materials
KPI	Key Performance Indicators
LC_{50}	Lethal Concentration (causing 50% mortality)
LT-PEMFC	Low temperature polymer electrolyte membrane fuel cells
MCFC	Molten carbonate fuel cells
MEA	Membrane electrode assemblies
MW	Molecular weight
MWD	Molecular Weight Distribution
NMP	*N*-methyl-2-pyrrolidone
ODC	Oxygen-depleted cathode
OECD	Organisation for economic co-operation and development
OEM	Original equipment manufacturers
PAFC	Phosphoric acid fuel cell
PBI	Polybenzimidazole
PBT	Persistent, bioaccumulative and toxic
PEEK	Polyether ether ketone

Acronym	Full name
PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
PEMWE	Polymer electrolyte membrane water electrolysis
PFA	Perfluoro alkoxy
PFAS	Per- and polyfluorinated substances
PFIB	Perfluoroisobutylene
PLC	Polymers of low concern
PTFE	Polytetrafluoroethylene
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RFG	Reactive Functional Group
RMOA	Regulatory management options analysis
SEA	Socio-economic analysis
SOFC	Solid oxide fuel cell
SOWE	Solid oxide water electrolyser
SVHC	Substance of very high concern
TFA	Trifluoroacetic acid
TFE	Tetrafluoroethylene
TGA	Thermogravimetric analysis
TSS	Thermal Specialised Solutions
vPvB	Very persistent and very bioaccumulative

1 Introduction

1.1 Background to the study

Per- and polyfluoroalkyl substances (PFAS) are a group of widely used synthetic organic chemicals whose properties are attributed to very strong, stable and apolar carbon-fluorine bonds. Five European countries made up of Norway, Germany, Denmark, Sweden and The Netherlands are currently preparing a restriction dossier due to be published in January 2023 under the EU REACH Regulation (EC) 1097/2006 (REACH). In the Registry of Intention of the PFAS restriction[1], PFAS are defined as "fluorinated substances that contain at least one fully fluorinated methyl (CF_3^-) or methylene (CF_2^-) carbon atom (without any H/Cl/Br/I atom attached to it)". This definition is similar to the Organisation for Economic Co-operation and Development (OECD) definition[2] that specifies a few noted exceptions, being "any chemical with at least a perfluorinated methyl group ($–CF_3$) or a perfluorinated methylene group ($–CF_2–$) is a PFAS." The polymer subject of this study is the high-performance proton exchange membrane Nafion™ that falls under this PFAS definition.

1.2 Study objectives

This study aims to objectively demonstrate the impact of a potential REACH Restriction of PFAS on a specific Chemours APM division and its downstream customers. The overall objective of this study is to develop a Socio-economic Analysis (SEA) for the continued use of Nafion™ versus the non-use scenario. The non-use scenario used in this study is envisaged as a complete ban of PFAS from 2025.

In particular, this study aims to develop a SEA for Nafion™ when used in the production and use of hydrogen gas as a green fuel, with an emphasis on the use of green hydrogen in the transport sector.

1.3 Approach and methodology

The RPA study team has collected and analysed data to answer the study objective. Data has been collected on the:

- Applications relevant to the study to understand the end-uses and actors in the supply chain;
- Alternatives to the substances that are under investigation or currently available;
- Response of businesses and society to a Restriction, to quantify impacts and compare to other regulatory measures.

Several data sources were used to obtain relevant information concerning the properties of PFAS in the hydrogen economy sectors including:

- Analysis of the grey and academic literature for chemical and mechanical properties of the substances under study;

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1 Registry of Restriction intentions until outcome found here https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e18663449b accessed November 2022

2 OECD. Series on Risk Management No. 61, 2021. available at https://www.oecd.org/env/ehs/risk-management/series-on-risk-management-publications-by-number.htm accessed November 2022

- Questionnaires, interviews and data collected via responses to our questions in consultation with Chemours APM and its subject matter experts, as well as their downstream customers.

1.4 Structure of this report

The structure of the remainder of this report is as follows:

- Section 2 Substance within the Scope of the Study: describes the structure, properties and regulatory context of Nafion™;
- Section 3 Chemours: describes the processing activities at Chemours' EU sites which involve Nafion™;
- Section 4 Sectors and uses for Nafion™ IXM: discusses the role of Nafion™ in the hydrogen economy;
- Section 5 Hazard properties: describes the hazards associated with Nafion™, their release to the environment and the release of residual monomers;
- Section 0
- Analysis of Alternatives: alternative materials to Nafion™ are examined in their ability to replace PFAS in the use cases within the scope of this study. Alternative technologies are also considered in the case of the hydrogen economy;
- Section 7 Continued use scenario: assesses the socioeconomic landscape within Chemours APM and its downstream users should an exemption to the PFAS restriction be provided for the use cases in the scope of this study;
- Section 8 Non-use scenario: assesses the socioeconomic landscape of within Chemours APM and its downstream users should a PFAS restriction prohibit the use of Nafion™ in the use cases within the scope of this study;
- Section 9 Conclusions: information gathered in this study is collated and a final commentary is made on the availability of alternatives and the overall effects of a PFAS ban versus the continued use scenario.

2 Substance within the Scope of the Study

2.1 Fluoropolymers

The polymer within the scope of this report is Nafion™ ion exchange membranes (IXM). The polymer belongs to a group of polymers known as fluoropolymers that falls under the classification known as per- and polyfluoroalkyl substances (PFAS) according to the Organisation for Economic Co-operation and Development[3] (OECD) definition, as it contains a fully fluorinated methyl group (-CF_3). Nafion™ is a copolymer, meaning that it is formed from two or more different types of monomers, i.e. tetrafluoroethylene (TFE) and perfluorosulfonic acid alkenes.

Fluoropolymers are not subject to registration under REACH. As such, a full picture concerning the production tonnage volumes of these substances in the EU is not complete. However, a recent SEA conducted by PlasticsEurope indicates that the production and import values of fluoropolymers in the EU were €1.03 billion and €270 million respectively in 2020[4]. Polymers, including fluoropolymers, are not considered of high concern toxicologically due to their high molecular weights which make transport across biological membranes such as the skin or gut-lining unlikely[5].

Fluoropolymers possess properties that are dependent on the presence of uniquely stable carbon-fluorine bonds providing them outstanding chemical properties making them a high-performance and unparalleled family of substances. This set of unique properties includes durability, mechanical strength in harsh conditions, as well as chemical inertness, non-wetting, non-stick and high resistance to temperature, fire, and weather.

Due to their properties, fluoropolymers have applications in many sectors including automotive, aerospace, environmental control, energy production and storage, and electronics as well as the broad chemical and pharmaceutical industries that are not easily replaceable with other substances or materials[6]. As a result of their high-performance and fine-tuned structure, fluoropolymers are typically expensive materials. Recent polymer price index data indicates that PTFE generally costs more than ten times that of its non-perfluorinated analogue, polyethylene[7]. Their ubiquitous use in demanding industries despite their high-cost highlights that fluoropolymers are in many cases the only polymer solution which provides suitable properties for certain applications.

2.2 EU Regulatory context

Since the announcement of the five countries' intention to publish a broad restriction of PFAS[8] in the EU, industry has maintained that fluoropolymers be excluded from the group for several reasons. An

3 https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?cote=ENV/CBC/MONO(2021)25&docLanguage=En#:~:text=The rationale behind the revision,noted exceptions%2C any chemical with accessed September 2022

4 https://fluoropolymers.plasticseurope.org/index.php/fluoropolymers/irreplaceable-uses-1/reports-policy-documents/socio-economy-analisis accessed November 2022

6 https://www.sciencedirect.com/topics/materials-science/fluoropolymer

7 https://www.plasticportal.eu/en/cenove-reporty

8 https://echa.europa.eu/registry-of-restriction-intentions/-/dislist/details/0b0236e18663449b accessed September 2022

independent regulatory management options analysis (RMOA)[9] was commissioned by PlasticEurope's Fluoropolymers Product Group (FPG), which concluded that restriction under REACH was not an effective tool for the adequate risk management of these substances and does not align with the objectives to ensure a higher level of human health and environmental protection in the EU. Instead, the PFG propose a broad derogation for fluoropolymers, supplemented by a Voluntary Industry Initiative to ensure that industry will address the situations of concern related to the manufacture and use of fluoropolymers.

2.3 Nafion™ structure and properties

Nafion™ membranes (CAS 31175-20-9, EC 680-985-7) are made from a perfluorosulfonic acid alkene /polytetrafluoroethylene (PTFE) copolymer (Figure 2-111Figure 2-11) and are used as ion exchange materials in a number of chemical and electrochemical processes due to their ion transport capabilities. Nafion™ is manufactured in the USA and then imported into the EU, where it sold in various forms by Chemours. Depending on the application, these forms are:

- **Ion exchange membranes (IXMs):** For application as a separator and solid electrolyte for the transport of protons and other ions in electrochemical cells.
- **Reinforced membranes:** Utilising strong and durable materials to allow for mechanical stabilisation of a polymer, reducing degradation, enhance durability and allowing boarder operating ranges.
- **Dispersions:** A system that allows particles of one material to disperse in a continuous phase to another. Nafion™ dispersions are used as binders to create catalyst coated membranes.
- **Resins:** Allows for the support of a structure and medium for ion exchange.

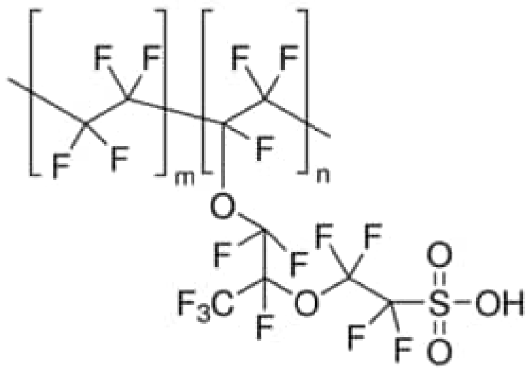

Figure 2-11: Structure of Nafion™ IXM
Source: sigmaaldrich.com/GB/en/product/aldrich/274674 accessed July 2022

The products which fall into the scope of this assessment are specifically Nafion™ IXMs. Following is a description of the properties of Nafion™ which make it a suitable material for its application as an ion exchange membrane.

9 https://fluoropolymers.plasticseurope.org/application/files/5416/5104/8333/20211104_FP_RMOA_Final_3.pdf accessed September 2022

Nafion™ has good mechanical properties such as tensile strength and flexibility which makes its membranes particularly durable despite their low thickness. Nafion™ also shows high stability to many harsh chemicals and is able to absorb water which gives it its proton conducting properties. Some of the main physical properties of Nafion™ membranes are shown in Table 2-1.

Table 2-1: Properties of Nafion™ IXM Membranes	
Property	**Value**
Thickness	22-254 µm
Appearance	Translucent, solid film
Basis weight (g/m^2)	44-500
Melting point (°C)	>200
Solubility in water	Insoluble
Tensile Strength (MPa)	38-43 (MD), 41-32 (TD)
Elongation at break (%)	182-343 (MD), 89-352 (TD)
Thickness increase (from 50% RH, 23°C to water soaked)	10%
Thickness increase (from 50% RH, 100°C to water soaked)	14%
pKa	-6
Source documents https://fuelcellsetc.com/helpful-tools/nafion-membrane-comparison-table/ accessed July 2022	

Nafion™ membranes are sold by Chemours in a range of grades and thicknesses as to be tailored to specific application needs. Nafion™ membranes can be reinforced or further chemically stabilised to meet the requirements of the end use application (Table 2-2). Further details on the common uses of Nafion™ are discussed in Section 4.

Table 2-2: Nafion™ grades			
Grade	**Description**	**Chemically Stabilised**	**Common Use(s)**
NR211	25-micron thickness	Yes	Energy storage, fuel cells
NR212	50-micron thickness	Yes	Energy storage, fuel cells
Unreinforced membranes			
N115	127-micron thickness	Yes	Energy storage, hydrogen generation, various electrolytic processes
N117	183-micron thickness	Yes	Energy storage, hydrogen generation, various electrolytic processes
N1110	254-micron	Yes	Hydrogen generation, various electrolytic processes
Reinforced membranes for specialty applications			
N324	High strength, high anion rejection membrane	No	Various electrolytic processes
N424	High strength membrane	No	Various electrolytic processes
N438	Highest strength, flatter profile than N424 membrane	Yes	Chlorine from hydrochloric acid using oxygen-depleted cathode (ODC) technology, various electrolytic processes
N551	High strength membrane with gas-release coatings	No	Chlor-alkali for potassium service, various electrolytic processes
Source documents https://www.nafion.com/en/products/sulfonic-membranes accessed July 2022			

Nafion™ is classed as an ionomer material since it is a copolymer of both neutral TFE and anionic perfluorosulfonic acid alkenes. Since the sulfonate groups are polar, Nafion™ is able to absorb water into the polymer structure. The resulting microstructure after hydration consists of well defined 'channels' of water throughout the material. It is these water channels which allow the transport of protons across the membranes.

Many different ionomer membranes and materials exist with varying degrees of commercial availability, however fluoropolymer IXM membranes like Nafion™ are particularly unique; like-like intermolecular attractions between the apolar perfluorinated polymer chains and like-like intermolecular attraction between the polar sulfonate side chains forms extremely well defined and ordered polar and apolar regions within the structure. These domains are less well defined in non-fluoropolymer ionomer materials since there is less of a polarity difference between the polymer backbone and the polar side chains.

Nafion™ is also sold as dispersions in water. Nafion™ dispersions are colloidal mixtures of microscopic particles of solid Nafion™ suspended in water. While not directly within the scope of this study, these dispersions are generally used alongside IXMs as functional binding agents for adhering catalysts to the Nafion™ membrane, as well as multiple other electrochemical applications. The use of Nafion™ as a binding agent instead of a different polymer ensures that proton conductivity is retained between the membrane and catalyst.

Nafion™ resins typically take the form of small polymer beads and are used as non-electrochemical ion exchange materials which have uses across multiple sectors, but are most commonly seen in chemical and pharmaceutical industries. Nafion™ resins do not have strong associations with fuel cell or water electrolysis applications, and are therefore considered to be out of scope for this report.

3 Chemours’ sites and Corporate Responsibility Commitment

3.1 Chemours sites in Europe

Chemours has PFAS related manufacturing and blending activities in three sites in Europe: Dordrecht in the Netherlands, Villers-St-Paul in France, and Mechelen in Belgium. Advanced Performance Materials (APM) division operates at all three sites. The Dordrecht site is shared with the Thermal & Specialised Solutions (TSS) division of the company, but the majority of the site is used for the manufacture of fluorinated monomers, fluoropolymers and fluoroelastomers. Nafion™ materials are not currently produced at any of Chemours European locations.

Nafion™ is imported into Europe from the United States in varying forms such as pellets, powders, membranes, or dispersions, with Nafion™ products being directly shipped to customers. Any waste is disposed of through authorised waste handling companies.

3.1.1 Emissions abatement

There are no emissions pertaining to the manufacture of Nafion™ ion exchange membranes in Europe. All processes related to the manufacture of Nafion™ polymer and its conversion into membranes takes place in North America.

While there is processing of monomers, polymerisation aids and other fluoropolymers and fluoroelastomers at the Dordrecht site, this is out of the scope of the study and emissions abatement will only be discussed briefly.

Chemours has made a 2030 Corporate Responsibility Commitment[10] (CRC) to reduce greenhouse gases produced during manufacture by 60% relative to a 2018 baseline and to achieve net-zero operation emissions by 2050. Additionally, Chemours is looking to reduce air and water process emissions of fluorinated organic chemicals by 99% and to reduce their landfill volume by 70% relative to a 2018 baseline.

For air and water process emissions of fluorinated organic compounds, Chemours has already achieved a 40% reduction relative to the 2018 baseline. These values are presented within the CRC report.

These goals are being achieved through the installation of abatement systems to reduce fluorinated organic compound emissions to both air and water. Chemours manufacturing plant at Dordrecht has emissions currently below the tightened environmental permit levels.

In 2021, improvements to water treatment processes were made at three of Chemours’ sites. These improvements include the thermal destruction of addition emission streams, installation of adsorption technology for aqueous waste streams and recovery to reuse in the chemical manufacturing process[4].

[10] https://www.chemours.com/en/-/media/files/corporate/crc/2021/chemours-responsibility-commitment-report.pdf?la=en&rev=092cd1b8ba98433bb45ab6c46918b3f9 accessed August 2022

The exposure risks to workers are mitigated through measures depending on the physical state of the PFAS material, potential hazards of the material, and the degree of potential exposure. All workers working closely with these hazardous materials are fully trained on the hazards, procedures and protective measures that should be taken. Protective measures put in place to protect workers from exposure include dermal and respiratory personal protective equipment or the use of ventilation. Each facility using PFAS materials have risk assessments performed that are done to evaluate the potential for worker exposure and to ensure these risks are controlled. The chemical processes using PFAS materials are within closed systems. If these closed systems need to be opened for maintenance or sampling of the chemical process for example, the requirements for opening the system are defined in authorised operating procedures or permits.

4 Sectors and uses for Nafion™ IXM

4.1 Discussion on all uses

Nafion™ ion exchange materials are used in a variety of industrial and academic applications. These applications include:

- Electrodialysis
- Electrochemical sensing equipment
- Microfiltration
- Pervaporation
- Water treatment
- Chlor-alkali process
- Polymer electrolyte membrane water electrolysis (PEMWEs)
- Polymer electrolyte membrane fuel cells (PEMFCs)
- Redox flow batteries

The latter three of these applications relate to the storage and use of renewable energy and as such are key drivers to shift to sustainable clean energy. Nafion™ IXMs are an integral part to the functionality of these energy applications. The use of ion exchange membranes within the renewable energy lifecycle is depicted in Figure .

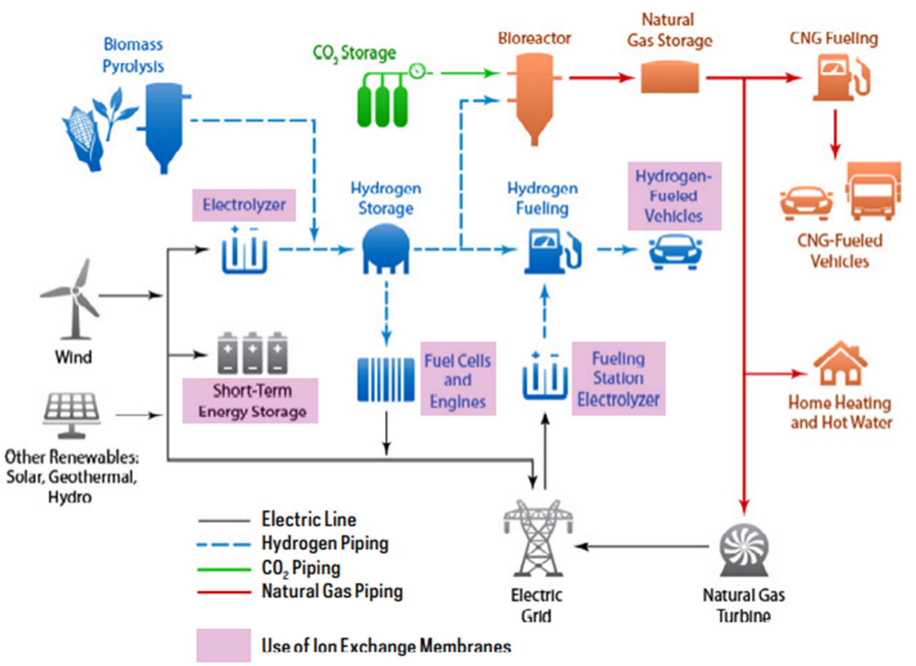

Figure 4-1: Diagram depicting the areas in which PEMs are used within the energy sector.
Source: Economic and Environmental Improvements with Versatile Membranes – Chemours Whitepaper

Of the diverse applications of Nafion™ membranes, this study focusses specifically on the main applications which are directly related to the energy sector:

- **Fuel cells:** electrochemical cells that convert chemical energy from a fuel source into electrical energy[11].
- **Water electrolysers:** A cell in which electrical energy is used to split water into hydrogen and oxygen[12].

The following sections of this chapter provide a more in-depth description of each of these end use areas, as well as the current status of the renewable energy landscape in the context of the end uses of Nafion™ membranes.

4.2 Hydrogen Economy

Renewable or green hydrogen is defined as hydrogen which is formed using energy provided by renewable sources such as wind or solar energy. Renewable hydrogen is normally generated by the electrolysis of water, as opposed to less sustainable methods of hydrogen production like the reformation of methane or gasification of coal. Hydrogen produced by the electrolysis of water powered by renewable sources can therefore be seen as a reliable chemical storage medium for renewable energy sources which can be intermittent and unreliable (e.g. wind and solar). Renewable hydrogen can be used as a fuel in a variety of applications, including home water heating systems, electrochemical power generation, fuel cell vehicles (FCV) and in internal combustion engines (ICEs) which have been modified to use hydrogen has as a fuel. Renewable hydrogen also has the potential to decarbonise some high-CO_2 industries such as the manufacture of steel, where hydrogen can both be used as a replacement for fossil fuels in blast furnaces and as a reducing agent to convert iron ore into metallic iron[13].

4.2.1 European strategic goals concerning the hydrogen economy

Hydrogen is projected to play a key role in a future climate-neutral economy, enabling emission-free transport, heating, and industrial processes. **The EU Hydrogen Strategy[14]** and the **European Clean Hydrogen Alliance[15]** adopted in July 2020 were developed to establish objectives to facilitate investments in clean hydrogen. Clean hydrogen produced by water electrolysis and hydrogen fuel cells are examples of capturing energy from renewable energy sources with zero greenhouse gases (GHG) emissions.

In 2020, the European Commission was predicted to invest €450 billion by 2050 for the research and development of clean hydrogen energy[16]. Part of this investment included the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) (now known as the Clean Hydrogen Partnership) under the European Horizon 2020 and Horizon Europe (2021-2027) which aimed to accelerate the fuel cell market by

11 https://www.britannica.com/technology/fuel-cell accessed September 2022
12 https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis accessed September 2022
13 https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf
14 https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf accessed September 2022
15 https://single-market-economy.ec.europa.eu/industry/strategy/industrial-alliances/european-clean-hydrogen-alliance_en accessed September 2022
16 https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf accessed September 2022

introducing efficient conversion technologies to combat carbon dioxide emissions, reduce hydrocarbon use and to stimulate economic growth[17,18].

Since 2020, these goals have progressed and evolved alongside consequences from the COVID-19 pandemic and the Russian invasion of Ukraine. In response to these major events, new initiatives have been put into place with an emphasis on accelerating hydrogen production and use with short term goals, mostly to be achieved by 2030.

There has been a drive to reduce or remove the EU's dependence on gas and oil imports, particularly from Russia. The EU currently imports 90% of its gas supply, 45% of these imports are provided by Russia as well as 25% and 45% of oil and coal imports respectively. The reduction of this import dependence is to be supported by the **REPowerEU** Joint European action for more affordable, sustainable, and secure energy. The EU's targets under REPowerEU are to increase renewables from 40% to 45% bringing the total renewable energy generation capacity to 1,236 GW by 2030[19].

Financing REPowerEU to reduce reliance on fossil fuel imports from non-EU countries is done through a total investment of €210 billion by 2027 across a variety of renewable energy vectors, where €113 billion is allocated to development of renewables and key hydrogen infrastructure, and €41 billion is allocated to adapting industries to use less fossil fuels.[20]

With these recent initiatives in mind, the EU values renewable hydrogen as a key aspect of achieving the Green Deal and ending reliance on fossil fuel imports from non-EU countries. The EU strategic goals relating to the production and consumption of renewable hydrogen set out in the **Green Deal**[21], the **Clean Hydrogen Partnership**[22] and **REPowerEU**[23] are ambitious, but achievable. These goals are made possible by the progression of PEMFC and PEMWE technology over recent years. This advancement in hydrogen production and consumption technology relies heavily on the use of fluoropolymer membranes such as Nafion™, without which, the necessary KPIs for PEMFCs and PEMWEs would not be met.

The **Hydrogen Roadmap Europe** prepared by the Clean Hydrogen Partnership predicts that by 2050 1.7 million HDV containing hydrogen fuel cells will be required on European roads to reach targets set under the Paris agreement[24]. Under Regulation (EU) 2019/1242 the European Union mandated that from 2025 CO_2 emissions from HDV's are to be cut by 30% by 2030[25]. As of 2019 it was estimated that 6.6 million medium-duty vehicles and HDVs are on European roads with around 3.3 million of a weight

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17 https://ec.europa.eu/growth/industry/strategy/hydrogen/funding-guide/eu-programmes-funds/horizon-europe_en accessed September 2022

18 https://www.fch.europa.eu/page/who-we-are accessed September 2022

19 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en accessed September 2022

20 REPowerEU financing factsheet found at: https://ec.europa.eu/commission/presscorner/detail/en/fs_22_3135 accessed September 2022

21 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en accessed September 2022

22 https://www.clean-hydrogen.europa.eu/index_en accessed September 2022

23 https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal/repowereu-affordable-secure-and-sustainable-energy-europe_en accessed September 2022

24 https://www.fch.europa.eu/sites/default/files/Hydrogen%20Roadmap%20Europe_Report.pdf accessed September 2022

25 https://www.howden.com/en-gb/articles/hydrogen-fuel-cells-heavy-duty-transport accessed September 2022

higher than 15 tonnes[26]. Collectively they represent 27% of road transport related CO_2 and around 5% of GHG emissions for the EU including the United Kingdom[27].

To ensure decarbonisation within Europe the European Commission announced the European Green Deal in 2019 which sets out policy initiatives to become climate neutral by 2050 and to reduce GHG emissions by 55% by 2030, such as the **Fit for 55**[28]. To ensure targets are achieved the EU has invested €60 billion to produce electrical and battery powered vehicles[29]. This increase is partly due to their ability to perform key functions while being environmental and energy efficient by 85-90% compared to internal combustion engines[30]. However, disadvantages include the availability of electrical refuelling stations which are still in the development stages, its shorter drive range and speed and long recharge time (4-6 hours)[31]. In this instance electrical and battery powered systems would not be economically beneficial for HDV due to the long distance that is required which is why with the growth in green hydrogen production, the transport industry is looking to transition to heavy duty hydrogen fuel cell vehicles (HDFCV). This will be a key pillar to achieving the goals of the fit for 55 plan. In 2021 the fleet size of HDFCVs was measured at just under 2,000 vehicles[32] with a fleet size of nearly 17,000 for LDFCVs[33]. Through use of industry insight data supplied to RPA the following annual estimate for the fleet size and sales of HDFCVs has been derived. Note all figures have been rounded to three significant figures

Table 4-1: Heavy duty fuel cell vehicle fleet size and annual sales estimates

Year	HDFCV fleet size	HDFCV sales
2022	4,570	2,580
2023	6,250	1,680
2024	9,260	3,010
2025	24,400	15,200
2026	119,000	94,200
2027	362,000	243,000
2028	735,000	374,000
2029	1,360,000	625,000
2030	2,370,000	1,010,000
2031	3,380,000	1,010,000
2032	4,390,000	1,010,000
2033	5,410,000	1,010,000
2034	6,420,000	1,010,000
2035	7,430,000	1,010,000

Sources: IHS information with downstream value chain partners information and Chemours internal analysis
IHS GLOBAL MHCV PRODUCTION FILE WITH PROPULSION SYSTEM DESIGN AND GVW July 5 2022
RPA analysis

26 https://www.fch.europa.eu/sites/default/files/FCH%20Docs/201211%20FCH%20HDT%20-%20Study%20Summary_final_vs.pdf accessed September 2022
27 https://www.eea.europa.eu/themes/transport/heavy-duty-vehicles accessed September 2022
28 https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/ accessed September 2022
29 https://www.transportenvironment.org/discover/record-%E2%82%AC60bn-investment-electric-cars-and-batteries-europe-secured-last-year/ accessed September 2022
30 https://pod-point.com/guides/driver/benefits-of-electric-cars accessed September 2022
31 https://www.conserve-energy-future.com/advantages-and-disadvantages-of-electric-cars.php accessed September 2022
32 IHS information with downstream value chain partners information and Chemours internal analysis
33 IHS GLOBAL MHCV PRODUCTION FILE WITH PROPULSION SYSTEM DESIGN AND GVW July 5 2022

This transition to hydrogen fuel heavy duty vehicles will allow for very substantial CO_2 emission reductions and financial savings to be made from these reductions. In 2019 road transportation in the EU emitted nearly 793 million tonnes of CO_2 of which 27% was attributable to heavy duty vehicles (HDVs)[34]. Also, in 2019 there were just over 6.1 million HDVs on the roads in Europe[35], resulting in an average annual CO_2 emission value per HDV of 34.9 tonnes. From this and by using historic data from ACEA the RPA study team estimated the projected fleet size of HDVs and calculated the annual emissions they will generate if the entire fleet was non-renewable powered. HDFCVs emit no CO_2 at the point of use and as such the emissions that would not be occurring from these vehicles has then been calculated and valued by multiplying the tonnes of CO_2 saved by the World Bank price for CO_2 of €84[36]. This information is presented in the following table and note all values apart from totals have been rounded to three significant figures.

Year	HDV fleet size	HDV CO_2 emissions (t)	HDFCV fleet size	CO_2 emissions saved	Saved emissions value (€)
2022	6,450,000	225,000,000	4,570	160,000	13,400,000
2023	6,560,000	229,000,000	6,250	218,000	17,600,000
2024	6,670,000	233,000,000	9,260	323,000	25,100,000
2025	6,780,000	237,000,000	24,400	854,000	63,800,000
2026	6,880,000	240,000,000	119,000	4,150,000	298,000,000
2027	6,990,000	244,000,000	362,000	12,600,000	872,000,000
2028	7,100,000	248,000,000	735,000	25,700,000	1,710,000,000
2029	7,200,000	252,000,000	1,360,000	47,500,000	3,030,000,000
2030	7,310,000	255,000,000	2,370,000	82,800,000	5,080,000,000
2031	7,420,000	259,000,000	3,380,000	118,000,000	6,970,000,000
2032	7,520,000	263,000,000	4,390,000	153,000,000	8,710,000,000
2033	7,630,000	267,000,000	5,410,000	189,000,000	10,300,000,000
2034	7,740,000	270,000,000	6,420,000	224,000,000	11,800,000,000
2035	7,840,000	274,000,000	7,430,000	259,000,000	13,100,000,000
Total		3,496,000,000		1,117,305,000	61,989,900,000

Source: https://www.statista.com/topics/7968/transportation-emissions-in-the-eu/#dossierKeyfigures accessed December 2022
https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf
State and Trends of Carbon Pricing 2022 http://hdl.handle.net/10986/37455 accessed 2022 The nominal price per tonne of carbon emitted is said to be $87 USD/tCO2e, the price was converted to Euros was based on the exchange rate from US dollars to Euros on 10 August 2022 $1 = €0.97

As can be seen above the transition to HDFCVs vehicles could reduce CO_2 emission by over 1.1 billion tonnes over the assessment period. This would result in an estimated discounted saving of nearly €62 billion over the assessment period. In addition to this if the transport industry transitions to HDFCVs as estimated above would also mean CO_2 emissions at the point of use from heavy duty vehicles will be reduced to nearly zero post 2035.

[34] https://www.statista.com/topics/7968/transportation-emissions-in-the-eu/#dossierKeyfigures accessed December 2022

[35] https://www.acea.auto/files/ACEA-report-vehicles-in-use-europe-2022.pdf

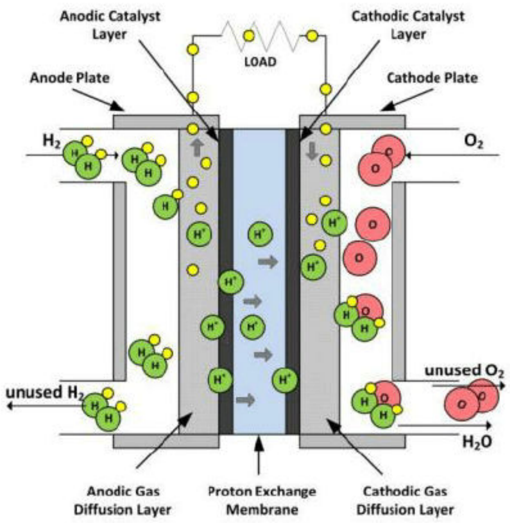
[36] State and Trends of Carbon Pricing 2022 http://hdl.handle.net/10986/37455 accessed 2022 The nominal price per tonne of carbon emitted is said to be $87 USD/tCO2e, the price was converted to Euros was based on the exchange rate from US dollars to Euros on 10 August 2022 $1 = €0.97

4.2.2 Overview of Nafion™ IXM applications within the scope of this study

4.2.2.1 Polymer electrolyte membrane fuel cells (PEMFCs)

PEMFCs are highly efficient tools for power extraction and are defined as electrochemical cells that convert chemical energy from a fuel source (hydrogen) to electricity[37] and can have up to twice the efficiency of conventional internal combustion engines[38]. PEMFCs can provide power to a range of applications with varying power requirements from <1 Watt to several megawatts. There are multiple classes of fuel cell available, however the most well-known of these is the low-temperature proton exchange membrane fuel cell (LT-PEMFC) which generally uses Nafion™ as the membrane material. LT-PEMFCs have gained a large amount of attention both in the academic, media and commercial landscapes over recent years. Their compact design and remarkably high gravimetric and volumetric energy densities have allowed them to be considered for use in commercial and personal vehicles.

PEMFCs are similar in mechanism to conventional batteries, where both fuel cells and batteries rely on a spontaneous electrochemical reaction between two or more species to generate an electromotive force, however some key differences separate the two technologies. Firstly, in batteries, the reactants are fully contained within the battery structure and are not replenished over time. Therefore, once all of the reactants have been consumed, no more electrical energy is released (i.e., a 'flat' battery), whereas in a fuel cell the reactants are fuels which are constantly pumped into the cell. As long as there is fuel in the tank, the cell does not stop providing power. Secondly, in a fuel cell, the products of the electrochemical reaction are removed via exhaust, whereas in a battery the reaction products remain within the cell. Hydrogen's high energy density and suitability as a fuel source for long-distance and heavy good transportation justifies rapid investment[39].



37 https://www.britannica.com/technology/fuel-cell accessed September 2022

38 Wang, Y., Pang, Y., Xu, H., Martinez, A., & Chen, K. S. (2022). PEM Fuel cell and electrolysis cell technologies and hydrogen infrastructure development – a review. Energy & Environmental Science, 15(6), 2288–2328. https://doi.org/10.1039/D2EE00790H accessed September 2022

39 Scott, K. (2020). Chapter 1: Introduction to Electrolysis, Electrolysers and Hydrogen Production. In RSC Energy and Environment Series (Vol. 2020-January, pp. 1–27). Royal Society of Chemistry. https://doi.org/10.1039/9781788016049-00001 accessed September 2022

Figure 4-2: Basic diagram of a proton exchange membrane in a fuel cell
Source: Abaspour, A., Tadrisi Parsa, N., & Sadeghi, M. (2014). A New Feedback Linearization-NSGA-II based Control Design for PEM Fuel Cell. International Journal of Computer Applications, 97(10), 25–32. https://doi.org/10.5120/17044-7354 accessed September 2022

An LT-PEMFC works using an input of hydrogen gas to the anode where a catalyst (platinum) oxidizes and splits the hydrogen molecules into protons (H^+) and negatively charged electrons (e^-). The e^- leave the anode following a circuit to the cathode generating work that can be used as electricity. Simultaneously, the protons will selectively move across the Nafion™ where they will combine with oxygen (O_2) and e^- at the cathode to form water. The mode of action of an LT-PEMFC is depicted in Figure .

Hydrogen fuel cells can be used in a wide range of applications including hydrogen powered semi-trucks, vans, buses, trains, passenger vehicles, drones, boats and are even being experimented in aerospace use[40].

Hydrogen fuel cells are significantly more energy dense and lighter in weight in comparison to traditional energy supplies (diesel 42.9 MJ/kg, hydrogen fuel cells 118 MJ/kg).[41] Furthermore, hydrogen HDV require the same amount of time as diesel HDV to refuel (up to 15 minutes large trucks) In a study comparing operational ranges between diesel, battery powered and hydrogen fuel cells in HDV's, hydrogen fuel cells had a longer average operation range of 1060-1770 km (660-1,104 miles) compared to battery powered vehicles 100-800 km (62-500 miles)[42]. Due to the weight and size of HDVs a heavier battery is needed for long ranges requiring more energy and power. Battery capacity for a HDV over an 800 km range is estimated to be 1000 kWh of energy requiring an average weight of 5500 kg to be dedicated to the battery making it less variable for large, long range HDV[43].

Large, stationary hydrogen fuel cells can also be used as backup generators to power places such as hospitals and data centres. However, the use of hydrogen fuel cells does not come without any challenges. Hydrogen must be kept in large stores to be a useful fuel for any of these applications, resulting in high pressure, cryogenic temperatures, and explosion hazards[44]. As a result of these difficult infrastructure limitations, current and near-future applications of hydrogen fuel cells will mostly be limited to sectors with centralised fuelling stations such as semi-trucks, buses, and taxis. On the other hand, with the vast amount of funding within the EU which has been set aside for developing the hydrogen infrastructure, as well as the growing public and private interest in hydrogen fuel, integration into everyday use may be accelerated in coming years.

4.2.2.2 Polymer electrolyte membrane water electrolysers (PEMWEs)

Water electrolysis is a process in which electricity is used to split water into hydrogen and oxygen. This process allows the production of hydrogen gas (denoted as green hydrogen) without the use of

[40] https://wha-international.com/10-hydrogen-fuel-cell-applications-you-might-not-know/ accessed September 2022
[41] https://rmi.org/run-on-less-with-hydrogen-fuel-cells/ accessed September 2022
[42] https://www.csrf.ac.uk/blog/long-haul-lorries-powered-by-hydrogen-or-electricity/ accessed September 2022
[43] Cunanan C, Tran M-K, Lee Y, Kwok S, Leung V, Fowler M. A Review of Heavy-Duty Vehicle Powertrain Technologies: Diesel Engine Vehicles, Battery Electric Vehicles, and Hydrogen Fuel Cell Electric Vehicles. *Clean Technologies*. 2021; 3(2):474-489. https://doi.org/10.3390/cleantechnol3020028
[44] https://wha-international.com/10-hydrogen-fuel-cell-applications-you-might-not-know/ accessed September 2022

less sustainable starting materials, as is the case when hydrogen is produced from reformation of methane or coal gasification (denoted as grey hydrogen). Water electrolysis can be performed using clean and renewable energy sources such as wind or solar power and therefore it is possible for electrolytically produced hydrogen to be a zero-carbon fuel. In addition, no damaging greenhouse gases are produced as a by-product in the electrolytic production of hydrogen, unlike conventional, non-electrolytic hydrogen production which forms large quantities of CO and CO_2[45].

The process of water electrolysis is depicted in Figure 4-3 where an input potential difference across the cell causes the water to split into positively charged hydrogen ions (H^+) and negatively charged electrons (e^-), and oxygen (O_2)[46]. Hydrogen ions will move across the proton exchange membrane to the cathode where it will react with the electrons at the cathode, reducing it to hydrogen gas (H_2)[47].

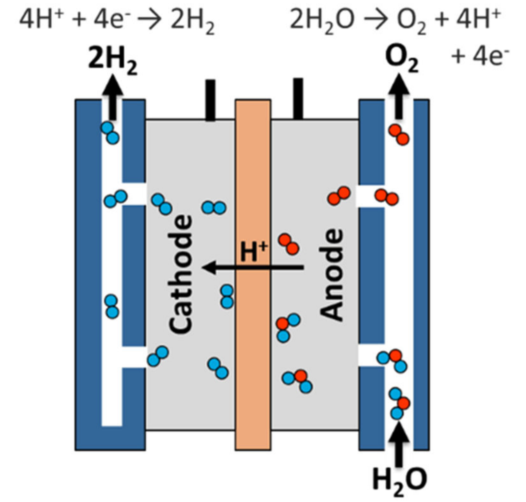


Figure 4-3: Basic diagram of water electrolysis
Source: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis accessed September 2022

The hydrogen gas generated can be used in many applications such as an energy source for electrical grids that are reliant on intermittent renewable energy sources (wind turbines and solar cells). It may also be stored and used in fuel cells[48]. Advantages of water electrolysis using PEM include greater energy efficiency, long storage periods and no GHG (greenhouse gas) emissions.

For fuel cells and electrolysers, the diagrams shown in Figure and Figure 4-3 show simplified diagrams for one electrochemical cell. The maximum voltages for these single cells are approximately 1 V. This voltage is far too low for fuel cell power applications, and in water electrolysers would only generate a small volume of H_2. These single cells are known as **membrane electrode assemblies (MEAs**), and consist of one anode, one cathode and one membrane with necessary ancillary equipment such as bipolar plates. To achieve the voltages required for commercial applications, many MEAs are connected together to form a **stack**. The stack size can be tuned to the required application, whether that be voltage for power output or for a specific hydrogen production volume. While the fundamental features of a fuel cell or electrolyser are met in the stack, multiple items of ancillary

45 https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis accessed September 2022
46 https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis accessed September 2022
47 https://www.intechopen.com/chapters/62151 accessed September 2022
48 https://www.nafion.com/en/applications/hydrogen-production accessed September 2022

equipment are also required for operation of the cell. This ancillary equipment is known as the balance of plant (BoP) and includes heat and water management systems, pumps and the overall framework for the cell. A stack which has been fitted with its full BoP is known as a **module**. The module is the final product and is ready to be installed in the application. These terms apply to most fuel cell and water electrolyser systems, whether or not they use fluorinated membranes such as Nafion™. In many systems, the overall module size and weight can vary depending on the additional BoP which is included to meet specific functionality requirements, but generally the BoP can add significant weight and volume to the system. This is an important consideration, particularly when developing fuel cells for transport applications where a high weight to power ratio is crucial to the design of an efficient vehicle.

4.2.2.3 Other application using Nafion™

Chloralkali process

The chloralkali process is the principally used electrolytic method of producing both chlorine gas and sodium hydroxide. The chloralkali process produces these products by applying an electrical potential across a sodium chloride solution where chlorine gas is produced at the anode and sodium hydroxide is produced at the cathode. Approximately 20 million tonnes of chlorine and sodium hydroxide are produced within the EU each year using the chloralkali process[49]. Chlorine made from the chloralkali process is used mainly within the production of PVC plastics and epichlorohydrin, a precursor for epoxy resin manufacture. Sodium hydroxide produced by this method is used widely within the production of aluminium and other metals, as well as pharmaceutical, food, paper and the fuel cell and electrolyser industry.

The chloralkali process historically used mercury as the cathode and as a method of separating sodium hydroxide from the electrolytic cell. However, the use of mercury in chloralkali cells has been phased out due to concerns over mercury pollution into the environment and has largely been replaced by membrane technology. Nafion™ and other similar perfluorinated ion exchange membranes are seen as the best technology available for the chloralkali process as they allow transport of sodium ions across the electrolytic cell without allowing mixing or reaction between the produced sodium hydroxide and chlorine gas. In addition, the use of membrane technology reduces the energy used to run the chloralkali process by about a third when compared to mercury cells.

In comparison to mercury, Nafion™ membranes for the chloralkali process present a significant reduction in the risk to human and environmental health. In addition, Chemours have worked closely with the chloralkali industry to ensure that the membrane is recycled at its end of life and is repurposed into new membranes for further application within industry.

The chloralkali process also produces a stoichiometric amount of hydrogen gas during operation as a by-product which can then be purified and used within hydrogen economy applications as described earlier in this section.

Redox flow batteries

A redox **flow battery** is a rechargeable battery using oppositely charged chemical solutions to generate and store electricity. The catholyte and anolyte are chemicals in different oxidation states. Some common redox pairs are vanadium and vanadium (using the different valency states), iron and

[49] https://www.eurochlor.org/

chromium, and zinc and bromine[50]. When these electrolytes are pumped through the system charge is added or removed at the electrodes depending on the charge/discharge cycle[51]. They have life spans up to 30 years and are most often used in applications that require megawatts of power for a minimum of six hours and are promising alternative to lithium-ion batteries[52].

A diagram of a flow battery is depicted in Figure , showing the key components consisting of two half-cells (anode and cathode) separated by one or more cell stacks with a porous PEM membrane in the middle to keep the solutions from mixing and allow H^+ ions to flow across the membrane to maintain charge balance. As seen in the diagram, the solutions are pumped into the cell stack, during discharge the negatively charged ions oxidize giving up an electron that moves to the electrode and moves through a circuit producing electricity[53]. It is then received at the opposite electrode and flows into the positively charged solution where reduction takes place, and the ions accept this electron[54]. This process is then reversed during the charging cycle.

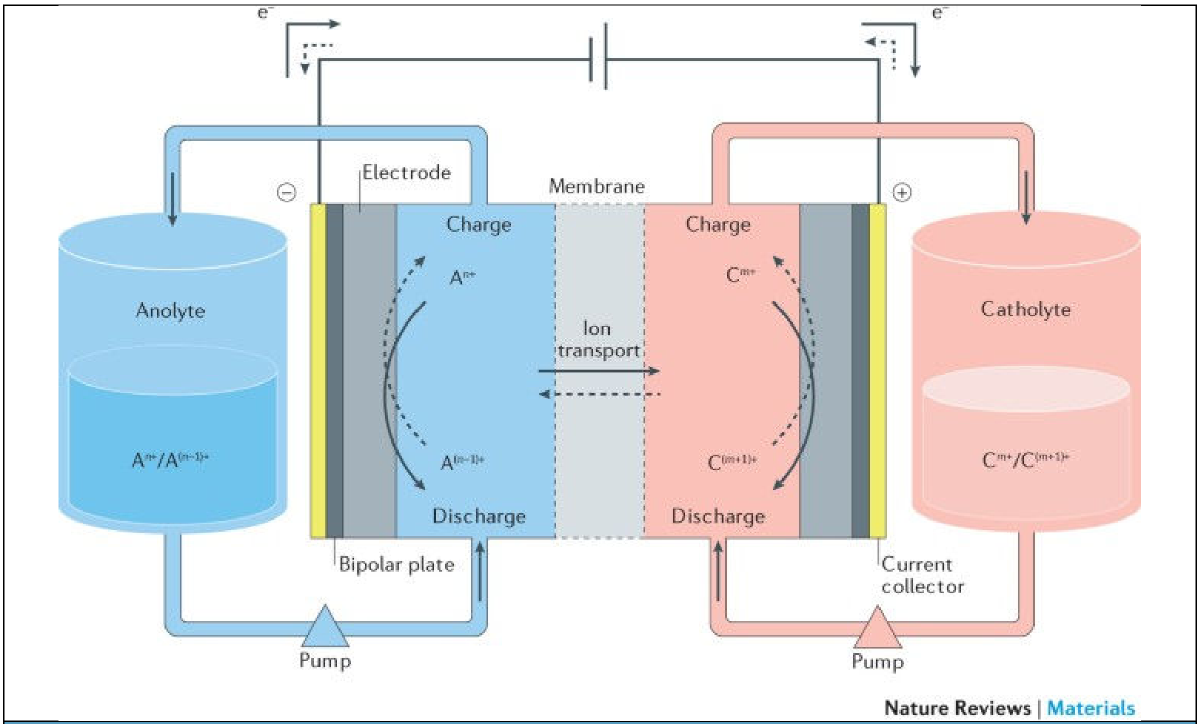


Figure 4-4: Basic diagram of a flow battery
Source: *https://www.nature.com/articles/natrevmats201680* accessed September 2022

50 https://flowbatteryforum.com/what-is-a-flow-battery/ accessed September 2022
51 nafion-evolution-of-energy-storage-white-paper.pdf accessed September 2022
52 https://www.powermag.com/flow-batteries-energy-storage-option-for-a-variety-of-uses/accessed September 2022
53 http://www.cei.washington.edu/education/science-of-solar/flow-battery/ accessed September 2022
54 http://www.cei.washington.edu/education/science-of-solar/flow-battery/ accessed September 2022

Flow batteries can be easily scaled up to unlimited energy capacity, by increasing the size of electrolyte storage tanks and the number of stacks. Other advantages include easy maintenance, extremely low fire hazard, fast recharge rates, non-toxic chemistry, and low environmental footprint[55].

Flow batteries are used in applications that require long-term uninterrupted power supplies such as factories and office buildings as well as being used for grid energy storage, for example being attached to a power plant or electrical grid.

4.2.3 Functionality of membranes in fuel cells and water electrolysers

Full cells and water electrolytes would not function without a membrane separating the anode from the cathode side. Proton exchange membranes (PEMs) are semipermeable membranes that are comprised of an organic linear chain backbone and anionic side chain groups, typically with a thickness of 10 to 300 µm[56]. The primary functionalities of a PEM are:

- To act as a proton conductor – the membrane should contain hydrophilic sidechains which can selectively and efficiently conduct protons with a low ionic resistance;
- Block direct electronic pathways – to allow current to flow across the load as useful energy, rather than allowing internal electron transfer and preventing short circuiting; and
- Act as a barrier – effectively separating the reactants as to prevent losses in current yield and prevent unwanted and hazardous mixtures of hydrogen and oxygen.

The Nafion™ membrane is a copolymer of polytetrafluoroethylene (PTFE) and perfluorosulfonic acid alkenes, therefore its backbone is hydrophobic. It also includes sulfonate (SO_3^-) side chains which are hydrophilic. The carbon-fluorine bonds make it extremely durable and chemical resistant, even when exposed to moisture. The sulfonated chains are anionic and tend to cluster together to form a microstructure which contains hydrophilic pockets. Due to the significant difference between the hydrophobicity of the PTFE backbone and the sulfonate groups, the hydrophilic domains are large and enable the flux of water and protons through the membrane. Each sulfonate group accommodates approximately 20 water molecules[57] (See Figure 4-5).

55 https://www.powermag.com/flow-batteries-energy-storage-option-for-a-variety-of-uses/ accessed September 2022

56 https://fuelcellsworks.com/knowledge/technologies/pemfc/ accessed September 2022

57 https://www.bcsd.org/site/handlers/filedownload.ashx?moduleinstanceid=1973&dataid=9790&FileName=fuel%20cell%20pdf.pdf accessed June 2022

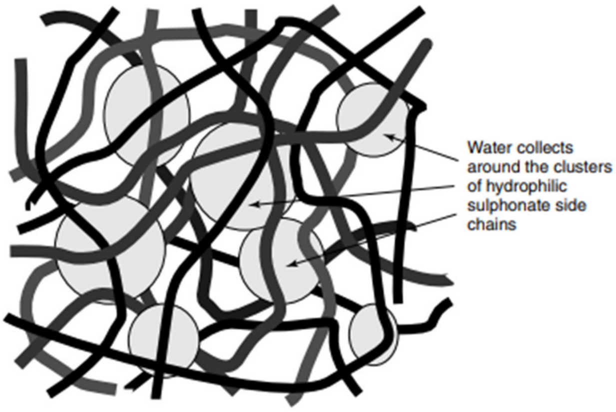


Figure 4-5: Long chain molecules containing hydrated regions around sulphonated side chains
https://www.bcsd.org/site/handlers/filedownload.ashx?moduleinstanceid=1973&dataid=9790&FileName=fuel%20cell%20pdf.pdf accessed June 2022

4.2.3.1 Key performance indicators in PEMFCs and PEMWEs and their relevance to the membrane material

One of the main measures of efficiency in a fuel cell or electrolyser is the overpotential. The overpotential of a system is defined as the additional potential beyond the theoretical thermodynamic value which must be applied to a system to obtain a target output.

In the context of electrolysers, the overpotential relates to the additional potential applied to the system in order to generate a specific volume of hydrogen gas. The overpotential of the system is related to a number of factors, including the efficiency of the catalyst, and most importantly in the context of this study, the ionic resistance. For example, if an electrolyser PEM degrades over its lifetime, the ionic resistance increases and the overpotential required to output the same volume of hydrogen gas will be higher. In the context of fuel cells, an increase in overpotential over time has the reverse effect, reducing the total power output of the fuel cell per kilo input of hydrogen.

In the transport sector, the main benchmarks for overall fuel cell performance are the specific power and energy densities. The specific power density of a fuel cell is the amount of electrical power produced by the fuel cell per unit mass. A high specific power density means that the vehicle will have a high acceleration, for example, internal combustion engines may have a specific power density of *ca.* 0.5-1 kW/kg. Specific energy density is the amount of chemical energy that can be converted to electrical energy per unit mass. A high specific energy density means that the vehicle will have a high range before refuelling. Fuel cell vehicles have a range comparable to that of internal combustion engines since both technologies store their chemical energy as an external fuel.

In the case of water electrolysers, a hydrogen production facility is normally stationary, so the mass of the system is less important. A more appropriate measure of efficiency is the volumetric power density which relates to the amount of hydrogen that can be produced per unit volume of space taken up by the electrolyser. The volumetric power density of water electrolysers becomes a particularly important factor when considering hydrogen refuelling stations in busy metropolitan areas, where both the demand for fuel and the cost of space is high.

The performance of the membrane is an intrinsic factor in keeping power and energy density metrics high. If the membrane performs poorly, the output voltage of the cell will be reduced and a larger stack and module size will be required, meaning the mass and volume of the cell will be higher for the same power output. Additionally, PEMs should be durable and have high stability under oxidising and reducing conditions and typically operate within 80°C to 100°C for long periods of time. More information will be given on the PEM functionality in Section 6.1.1.

4.2.4 Supply chain

The supply chain for both fuel cells and water electrolysers can be seen in **Error! Reference source not found.**.

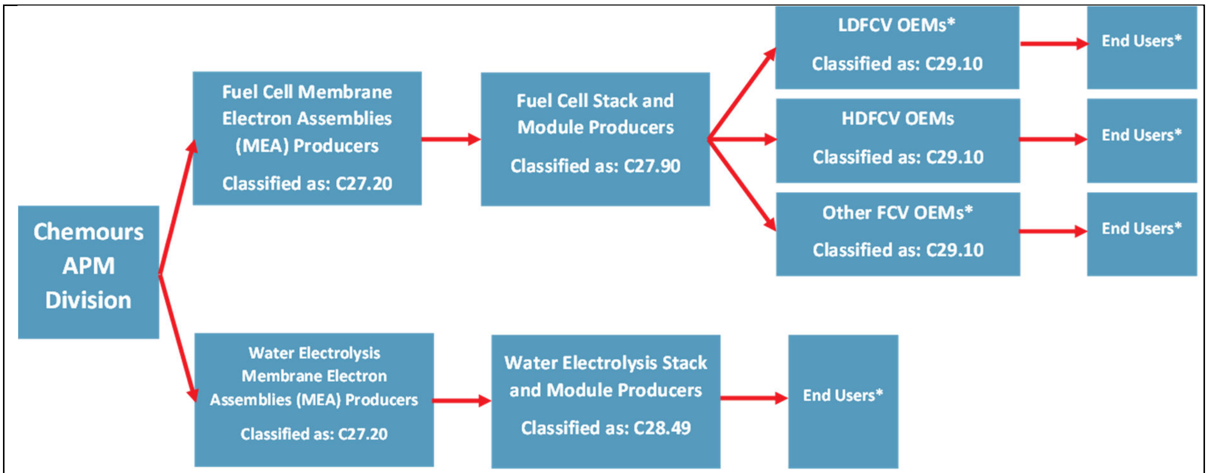


Figure 4-6: Chart demonstrating the supply chains involved with the use of Nafion™ membranes and dispersions for fuel cells and water electrolysis
Source: Consultation with Chemours APM and RPA study team analysis

A number of end users and OEMs (marked with an asterisk in the above figure) have been considered out of scope of this SEA and were not contacted during consultation. Similarly heavy-duty vehicle (HDV) OEMs were not contacted during consultation of this SEA however when the operations of fuel cell MEA and stack manufacturers were analysed only operations related to heavy-duty applications were considered. Also, it should be noted that MEAs produced for fuel cells and water electrolysis equipment are often manufactured by the same enterprises and as such these market segments have been amalgamated into one and are discussed as just MEA manufacturers together. The relevant NACE code classification which has been identified as covering products and enterprises operating within these market segments have also been included in the above figure.

5 Hazard properties

5.1 Introduction

This section will present the hazard properties of Nafion™. This includes Nafion™ constituent monomers, which could conceivably be present in the final membranes. Fluoropolymers are classed as PFAS, but often exhibit properties which separate them from small molecule PFAS such as F-gases or fluorinated solvents due to their reduced water solubility, volatility, and biological uptake. They are high molecular weight polymers and have been assessed according to assessment criteria to be classified as polymers of low concern (PLC). The OECD Expert Group on Polymers concluded that "Polymers of low concern are those deemed to have insignificant environmental and human health impacts"[58]. There has been enough data to develop a document with the criterion that qualifies a polymer as a PLC. The remainder of this section will discuss these criterions and present the key values for the substances within this study.

Due to the large molecular structure of polymers, they are considered too large to cross biological membranes and exhibit hazardous properties (>1000 – 10000 Dalton). Molecular weight is the most commonly used criteria when assessing polymers[28]. Polymers presenting the most potential health concerns will have a number average molecular weight (M_n) <1000 Dalton (Da) and oligomer content >1%[28]. Monomers, oligomers, and degradation products from the polymerisation process are smaller and therefore can potentially cross biological membranes and may then have the potential to be hazardous. It is important that the oligomer % and residual monomers are considered during the assessment, this is also called the leachability of the polymer.

The presence of Reactive Functional Groups (RFGs) can be associated with adverse human health and ecotoxicology[28]. The functional group equivalent weight (FGEW) determines if the RFGs are diluted by polymeric material to allow the polymer to be considered a PLC and is used as an indication of how reactive the polymer is[28].

The polymeric charge is important to consider because it can influence how a polymer acts and its properties. For example, cationic polymers have been associated with aquatic toxicity[28].

In summary, according to Henry et al. 2018 and the OECD[59], it can be inferred that the properties affecting a polymer assessment include the following:

- Molecular weight (MW): A polymer with a low molecular weight could mean the potential for health and ecotoxicological concerns.

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58 Henry, B. J., Carlin, J. P., Hammerschmidt, J. A., Buck, R. C., Buxton, L. W., Fiedler, H., Seed, J., & Hernandez, O. (2018). A critical review of the application of polymer of low concern and regulatory criteria to fluoropolymers. *Integrated Environmental Assessment and Management*, *14*(3), 316–334. https://doi.org/10.1002/IEAM.4035

59 *JOINT MEETING OF THE CHEMICALS COMMITTEE AND THE WORKING PARTY ON CHEMICALS, PESTICIDES AND BIOTECHNOLOGY DATA ANALYSIS OF THE IDENTIFICATION OF CORRELATIONS BETWEEN POLYMER CHARACTERISTICS AND POTENTIAL FOR HEALTH OR ECOTOXICOLOGICAL CONCERN JT03258707 Document complet disponible sur OLIS dans son format d'origine Complete document available on OLIS in its original format*. (2009). https://www.oecd.org/env/ehs/risk-assessment/42081261.pdf

- Polymer composition: This relates to the monomers, oligomers and processing aids used during polymerisation. These will have lower molecular weights potentially making them more hazardous.
- Polymer charge: Charge can influence how a polymer acts and its properties including, physical properties, fate, ecotoxicity, and human toxicity.
- Structural features: This includes its reactive functional groups (RFGs) and particle size.
- Solubility and stability: Low solubility in water and n-octanol demonstrate the inability of fluoropolymers to actively cross cell membranes and bioaccumulate. While stability shows the durability of the polymer and likelihood of breaking down into smaller molecules.

Each of these properties will be assessed for Nafion™ membranes.

5.2 Substance hazard properties

5.2.1 Nafion™ membranes (CAS 31175-20-9, EC 680-985-7)

Nafion™ membranes are composed of a PTFE (polytetrafluoroethylene) backbone with a perfluoroalkylether side chain ending in sulfonic acid groups. Nafion™ is the material of choice as proton exchange membrane used in fuel cells and water electrolysers. Nafion™ is available in membrane, dispersion, and resin forms.

5.2.1.1 Classification and labelling

Nafion™ ion exchange membranes are considered articles and therefore do not need to be REACH and do not have a harmonised classification and labelling under Regulation (EC) No. 1272/2008. Nafion™ has been notified by 38 importers and manufacturers to be Eye Irrit. (H319) and STOT SE (H335). However, it is not known in which state these hazards are notified (dispersion, resin,, membrane), nor is the target for the specific organ toxicity notified.

The representative EU Safety Data Sheet (SDS) for Nafion™ membranes indicates it is not hazardous[60].

Tetrafluoroethylene (TFE, CAS 116-14-3, EC 204-126-9) is one of the monomers used during polymerisation and is a REACH registered substance[61] and currently a harmonised classification and labelling under Regulation (EC) No. 1272/2008 is not published but has been adopted by The Committee for Risk Assessment (RAC). The Committee developed their opinion in December 2019[62] and was in agreement that the substance should be classed as carcinogenic category 1B under Regulation (EC) No. 1272/2008. The dossier evaluation has been concluded and the opinion adopted, however, it has not yet been published (as per September 2022). The registration dossier[63] classifies the substances as extremely flammable gas (H220), gas under pressure (H280), STOT SE 2 (H371, kidney), and carcinogenic 1B (H350). The latter is aligned with the adopted opinion of the RAC in an assessment of regulatory needs that was carried out in 2018.

60 Nafion™ N117 SDS No. 1745646-00011 Chemours; 25 June 2020
61 https://echa.europa.eu/registration-dossier/-/registered-dossier/15453
62 https://echa.europa.eu/documents/10162/becfc8d6-8a83-a81e-27d7-abadc6c7b585 accessed September 2022
63 https://echa.europa.eu/registration-dossier/-/registered-dossier/15453 accessed November 2022

Nafion™ assessment according to Polymer of Low Concern Criteria

A critical review of the hazard properties of Nafion™ was performed by Henry *et al* in 2018, and the summary of those results are presented in Table . The properties of Nafion™ do not exceed the threshold to be considered a hazardous polymer. However, it is possible that all fluoropolymers will soon require registration under REACH regardless of their PLC status.

Table 5-1: Assessment criteria for PLC classification	
Criteria	**Value**
Polymer composition (must have C, H, Si, S, F, Cl, Br, or I covalently bound to C)	Yes
Molecular Weight (MW) Characteristics:	
Weight average molecular weight (Mw)	10^5-10^6 Da
Molecular weight distribution	1.0-2.4
M_n > 1000 Da and oligomer content < 1%	Yes
Molecular Weight Distribution (MWD) ÷ number average M_n (M_n and heterogeneity of MW distribution indicate if majority are >1000 or <1000 Da, which could penetrate the cell)	Not available
Wt % oligomer (5% for <1000 Da oligomer, 2% for <500 Da oligomers)	Negligible
Polymer composition:	
Residual monomer	Not available
Residual PFAS surfactant	N/A (No surfactant used in Nafion™ production)
Ratio of residual monomers to MW (more low MW monomer content per mole increases bioavailability and hazard potential)	Not available
Polymer charge (cationic polymers associated with aquatic toxicity; polycationic with adverse human health effect)	Anionic
Reactive functional groups (RFGs) (some highly reactive functional groups associated with adverse human health and ecotoxicology effects, e.g., acrylates, isocyanates, anhydrides, aziridines)	Contains sulfonate functional groups, not considered RFG
Functional group equivalent weight (FGEW) (the lower the FGEW, the more reactive the polymer and the higher the potential for health and environmental impact)	>10^5 for RFG ~1000 $gmol^{-1}$ (g of polymer per mole of sulfonate groups)
Low molecular weight leachables (MW < 1000 Da able to enter cell)	<1 ppm
Residual monomers	<1 ppm
Ratio of residual monomers to molecular weight (typical value)	10^{-5}
Physico-chemical properties:	
Water solubility (water solubility <10 mg/L showed generally low health concerns; 10 mL/L to 10000 mg/L had potential health concern)	Practically insoluble or insoluble
Lipid solubility	Not available
Octanol- water partition coefficient, Log K_{ow} (higher K_{ow} associated with lipophilicity and a high potential to bioaccumulate or bioconcentrate)	N/A
Hydrolysis (breaking into M_n < 1000 Da increases hazard potential)	Stable
Light (hv) (breaking into M_n < 1000 Da increases hazard potential)	Stable
Biodegradation (aerobic and anaerobic) (breaking into M_n < 1000 Da increases hazard potential)	Stable
Thermal stability and normal operating temperatures	175°C under anhydrous conditions, 220-240°C for water or organic solvated membranes
Particle size (median mass aerodynamic diameter, MMAD, should be >5 µm)	N/A as membrane

Table 5-1: Assessment criteria for PLC classification	
Criteria	**Value**
Source documents: Henry, B. J., Carlin, J. P., Hammerschmidt, J. A., Buck, R. C., Buxton, L. W., Fiedler, H., Seed, J., & Hernandez, O. (2018). A critical review of the application of polymer of low concern and regulatory criteria to fluoropolymers. *Integrated Environmental Assessment and Management*, *14*(3), 316–334. https://doi.org/10.1002/IEAM.4035	

While there are concerns over polymers with reactive functional groups such as acrylates, isocyanates, anhydrides or azadrines, the sulfonate functional groups present in Nafion™ are not chemically reactive and are only able to facilitate ionic or dipole interactions.

Charged polymers can be of concern to aquatic life, however this is usually only the case for cationic polymers. Since Nafion™ is an anionic polymer, it is expected to be of low aquatic toxicity.

5.2.1.2 PBT/vPvB assessment for Nafion™

REACH Annex III and XIII present the persistent, bioaccumulative and toxic (PBT) and very persistent and very bioaccumulative (vPvB) criteria, and the information requirements that can be used in the PBT/vPvB assessment.

- P/vP – persistent: the half-life of Nafion™ is not measured but is expected to be in the order of years, therefore exceeding vP criteria. Therefore P/vP criteria are met.
- B/vB – bioaccumulation: Due to the large molecular weight of the substance it is not expected to bioaccumulate.
- T – toxicity: the substance is not classified as carcinogenic (category 1A or 1B), germ cell mutagenic (category 1A or 1B), or toxic for reproduction (category 1A, 1B or 2), nor is there other evidence of chronic toxicity, as identified by the substance meeting the criteria for classification: specific target organ toxicity after repeated exposure (STOT RE category 1 or 2). Nafion™'s lack of water solubility and other characteristics mean that it is likely the substance is not T.

Based on the above information, it is possible to conclude that Nafion™ is P, not B, and not T according to Annex III to the REACH Regulation. Similarly, it is possible to conclude that Nafion™ is vP and not vB. Overall, Nafion™ does not meet the PBT/vPvB criteria.

There is limited data available on the toxicity of Nafion™ to humans. Its large molecular weight means uptake would be difficult and it is unlikely to cross biological membranes. There is no data available on its bioaccumulation potential. Nafion™ is not at risk of being dispersed through air in the form of dust particles and therefore does not pose an inhalable risk to users.

Low molecular weight fluorinated monomers and the products of thermal decomposition of fluoropolymers, however, can be acutely toxic and harmful to health. Caution must be used when processing fluoropolymers in order for fluoropolymers to remain in their inert and non-hazardous state. Fluoropolymer handling guidelines[64] have been published and address the main routes for release of harmful substances from fluoropolymers.

If fluoropolymers such as Nafion™ are heated above their recommended processing temperature, there is a possibility for generating toxic decomposition products. These decomposition products can vary in concentration between fluoropolymers and their release can be dependent on the temperature, availability of oxygen, surface area etc. However, some common fluoropolymer degradation products and their hazards are listed in Table 5-2.

Table 5-2: Common fluoropolymer decomposition products and their hazards

Substance	Workplace exposure limits (TWA)	Hazard Properties
Carbonyl Fluoride (COF_2)	2 ppm	Acute Toxicity - Inhalation (Cat. 2) Skin Corrosion/Irritation (Cat. 1) Serious Eye Damage (Cat. 1) Specific target organ toxicity - Single Exposure (Cat. 1) (lungs)
Carbon Monoxide (CO)	25 ppm	H220 Flammable gases (Cat.1) H3 31 Acute toxicity - Inhalation (Cat. 3) H360D Reproductive toxicity (Cat 1A) H372 Specific target organ toxicity - repeated exposure, inhalation (Cat. 1)
Hydrogen Fluoride (HF)	3 ppm 2.5 mg/m^3	H300 Acute toxicity, Oral (Cat. 2) H330 Acute toxicity, Inhalation (Cat. 2) H310 Acute toxicity, dermal (Cat.1) H314 Skin corrosion (Sub-cat 1A) H318 Serious eye damage (Cat. 1)
Tetrafluoroethylene (TFE)	2 ppm	Flammable gases (Cat. 1) Carcinogenicity (Cat. 1) Specific target organ toxicity – Single exposure (cat. 2)
Perfluoroisobutylene (PFIB)	0.014 ppm (AEGL-2), 0.042 ppm (AEGL-3) (8 hour exposure)	Acute toxicity, Inhalation (Cat. 2)
Hexafluoropropylene (HFP)	No WEL available	Acute toxicity, Inhalation (Category 4), H332 Specific target organ toxicity - single exposure (Category 2), H371 Specific target organ toxicity - single exposure (Category 3), Respiratory system, H335 Specific target organ toxicity - repeated exposure (Category 2), H373
Source documents: Commercial material safety data sheets		

Sun and Wang investigated the thermolysis products of Nafion™ membranes[65]. Thermogravimetric analysis (TGA) showed three main stages of decomposition under a nitrogen atmosphere: 75-200°C,

[64] *Guide for the Safe Handling of Fluoropolymer Resins*. (2021). https://fluoropolymers.plasticseurope.org/application/files/6216/3178/0517/Fluoropolymers_Safe_Hand_EN__June_2021.pdf accessed September 2022

[65] Feng, M., Qu, R., Wei, Z., Wang, L., Sun, P., & Wang, Z. (2015). Characterization of the thermolysis products of Nafion membrane: A potential source of perfluorinated compounds in the environment. Scientific Reports 2015 5:1, 5(1), 1–8. https://doi.org/10.1038/srep09859

275-400°C and 420-600°C. The decomposition at lower temperature ranges is particularly important, since it is possible for thermolysis products to be released during processing and operation of Nafion™ and its technologies. The thermolysis products from the 75-200°C range were tentatively identified as perfluorinated carboxylic acids, specifically trifluoroacetic acid and perfluorooctanoic acid. Quantitative data on the amount of these products released is unavailable, but by TGA, approximately 3-5% of the total mass of Nafion™ was lost upon reaching 200°C.

The decomposition product of Nafion™ membranes, trifluoroacetic acid (TFA), is classified as a hazardous substance under Regulation (EC) No 1272/2008. The hazard classifications of TFA are as follows[66]: Acute toxicity, Inhalation (Category 4), H332 Skin corrosion (Sub-category 1A), H314 Serious eye damage (Category 1), H318 Long-term (chronic) aquatic hazard (Category 3), H412. There is currently no workplace exposure limit in place for TFA, however the pungent odour is detectable in low concentrations. The inhalation LC_{50} for rats at an exposure time of 4 h is 10.01 mg/L. There is no available data for the dermal or oral toxicity of TFA, however due to the gas phase nature of TFA release from Nafion™, these exposure routes are not likely.

Small fluoropolymer particles of diameter between 10 and 100 nm can be released from Nafion™ during hot processing methods[67]. While these particles themselves do not pose a hazard to health, they can act as carriers for radical species which would otherwise be too reactive to penetrate into the body. Johnston et al (2000) found that in isolation, fume gases or ultrafine fluoropolymers alone did not show significant toxicity in mice and rats. The combination of both ultrafine fluoropolymer particles along with thermolysis fumes was found to be significantly toxic, highlighting the synergistic toxicity between the two processing emission types[68].

5.3 Conclusions on Nafion™ hazards

Nafion™ itself is not an intrinsically hazardous material. Nafion™ membranes have been notified as skin and eye irritants, however tests with human volunteers have reported that that skin irritation is minimal. PBT and vPvB assessments have concluded that Nafion™ is persistent in the environment due to its extremely high stability. Since the polymer chains have a sufficiently high molecular weight, Nafion™ is expected to be neither bioaccumulative nor toxic. A report which undertook a PLC assessment on multiple fluoropolymers including ionomer membranes concluded that Nafion™ is a polymer of low concern, mostly due to the high molecular weight, low solubility and absence of reactive functional groups.

As is the case with all fluoropolymers, if Nafion™ is heated above its certified operating temperature, release of harmful compounds such as perfluorocarboxylic acids or HF may be possible. In addition, there are reports of adverse health effects when fluoropolymer particles are inhaled alongside degradation fumes.

[66] https://echa.europa.eu/information-on-chemicals/cl-inventory-database/-/discli/details/47316

[67] https://www.hse.gov.uk/research/rrpdf/rr539.pdf accessed July 2022

[68] Johnston, C. J., Finkelstein, J. N., Mercer, P., Corson, N., Gelein, R., & Oberdorster, G. (2000). Pulmonary effects induced by ultrafine PTFE particles. Toxicology and Applied Pharmacology, 168(3), 208–215. https://doi.org/10.1006/taap.2000.9037

The presence of residual monomers and processing aid within Nafion™ is a possible cause for concern, since these compounds can be toxic to humans. However, these compounds are normally removed from the polymer effectively and are only present in the final product in concentrations <1 ppm.

Overall, if Nafion™ is processed and used for its intended purpose, without exceeding normal processing temperatures, there is minimal risk to human health and does not pose the same risk as low-molecular weight PFAS substances within the scope of the proposed REACH restriction.

6 Analysis of Alternatives

This Analysis of Alternatives (AoA) provides an analysis of the feasibility of potential alternatives to Nafion™ IXM in the fuel cell, and water electrolysis sectors. It will assess the potential alternatives, economic feasibility, technical feasibility, availability, and hazard properties. As the proposed restriction covers all PFAS substances, the focus of this AoA will be on non-PFAS substances and therefore exclude in-kind alternatives. This section will be referenced in the non-use scenario to better predict the associated impacts of a potential restriction.

This section will describe ongoing research efforts which are seeking to replace fluorinated proton exchange membrane materials with non-PFAS alternatives which aim be used as a direct substitute in PEMFC and PEMWE technology.

In addition to alternative membrane materials, there is also a possibility of utilising alternative engineering solutions which do not make use of Nafion™ membranes such as alkaline fuel cells and water electrolysers, solid oxide fuel cells and electrolysers, high-temperature proton exchange membrane fuel cells and others. The performance criteria of these alternatives are compared to those of PEMFC and PEMWE technologies where appropriate, as well as their current technological status and use within the EU.

6.1 Alternatives to Nafion™ membranes in fuel cells and water electrolysers

The hydrogen economy sector is dependent on the use and production of green hydrogen to produce clean, sustainable energy. This is highly dependent on the use of proton exchange membranes, particularly Nafion™ IXM and other similar proton exchange polymers, due to the unique characteristics and functionalities delivered by this material. This section presents high-level screening of potential alternatives to Nafion™ membranes used in fuel cells and water electrolysers.

The importance of proton exchange membranes is not only relevant to hydrogen fuel cells but also in the complementary process of water electrolysis. Hydrogen fuel cells consume hydrogen to produce electricity while water electrolysers use electricity to produce hydrogen. The global decarbonisation goals mean the implementation of green hydrogen energy is at the forefront of emerging technologies and without the use of fluoropolymers not only will proton exchange membranes suffer but also other aspects of the fuel cell, including catalyst layers and the gas diffusion layers.

A discussion on the use of Nafion™ IXM in proton exchange membranes (PEMs) in fuel cell and water electrolyser stacks and modules is provided in Sections 4.2.2 and 4.2.3.

From desk-based research and consultation with downstream users of Nafion™ membranes, it is evident that there are currently no feasible alternatives to fluorinated proton exchange membranes available on the market which could be used as a direct replacement for fluoropolymer-based membranes within PEMFCs or PEMWEs, and therefore no market data is publicly available for these materials. This section will instead discuss the current state of academic research and development of novel, non-fluorinated alternatives and compare them to the functionality delivered by Nafion™ and other fluoropolymer alternatives.

The scientific literature is broad when considering alternative membrane materials. There are numerous innovations concerning non-fluorinated ion exchange membranes, most of which are based around phenylene-type hydrocarbon membranes. Research to improve the mechanical stability of hydrocarbon membranes under humid conditions remains one of the main focusses in this area. In particular, inclusion of inorganic materials such as clays and oxides into the polymer material have shown to improve physicochemical characteristics. Despite these numerous innovations, there is an important discrepancy between academic research materials and commercially viable alternatives, being that, in the research, a 'good' hydrocarbon membrane is one that has a lifetime of >500 hours. This value is an order of magnitude lower than the DoE targets, and 50 times lower than the accepted limit for Nafion™ membranes. For this reason, in the literature one may find many 'suitable' alternatives, but their performance over the extremely long lifetime requirements may not be up to commercial standards or may not even have been tested. In general, it is important to distinguish between the lifetimes of membranes when applied to a real system, versus laboratory tests. While some of the alternative materials discussed in the following section have demonstrated good lifetimes under laboratory conditions, this may not reflect their lifetime in a true application, where unpredictable cycling, weather conditions or general wear and tear may significantly reduce the membrane lifetime.

6.1.1 Performance requirements of materials used for proton exchange membranes in fuel cells and water electrolysers

In this section the functionality and performance of substances used in proton exchange membranes for hydrogen fuel cells and water electrolysis will be discussed. The membrane must perform within the module for a long period of time. While the US Department of Energy (DoE) ultimate goal for fuel cell lifetime is currently 8,000 hours for applications in an automotive application[69], the generally accepted standard amongst manufacturers is that a membrane should function for a minimum of 25,000 hours for commercial vehicles (buses, trucks, etc.) with some variability depending on the specific end-use application. Some fuel cell module manufacturers indicate Nafion™ and other similar perflourinated￼ alkene-based￼can even function for up to 80,000 hours of use. For personal vehicles, the average life expectancy for an internal combustion engine car is c.a. 320,000-400,00 km (200,000 – 250,000 miles), which relates to an approximate total running time of 5,000 hours based on an average speed of 80 km/h (50 mph). This value can be significantly higher for commercial transport such as semi-trucks which can easily run for 2,500 hours per year. If PEMFCs are to continue to be technically feasible, any alternative technologies or PEMFCs implementing alternative materials should have a minimum lifetime of 5,000 hours, and much longer for commercial vehicles.

The main functionality requirements which make Nafion™ and ideal membrane material which is suitable for the demanding requirements of use in PEMFCs and PEMWEs are described in Table 6-1. These are the criteria which must be satisfied by a potential alternative to be technically viable replacement.

Table 6-1: Essential membrane properties

Property	Description for PEMFCs	Description for PEMWEs
Proton conductivity	Allows protons from oxidised hydrogen gas (H_2) produced at the anode to migrate across to	The membrane must allow protons from the oxidation of water at the anode to migrate to

[69] https://www.energy.gov/eere/fuelcells/doe-technical-targets-fuel-cell-systems-and-stacks-transportation-applications accessed July 2022

Table 6-1: Essential membrane properties		
Property	**Description for PEMFCs**	**Description for PEMWEs**
	the cathode where they are combined with electrons and oxygen (O_2). The proton conductivity of a membrane should be >0.1 Scm^{-1} under operating conditions. In addition, the PEM must prevent permeation of the fuel gas (H_2) and the oxidant (O_2) across the membrane. Mixing of these gases from high gas permeability may reduce the efficiency of the MEA and increase risk of explosions.	the cathode where they are reduced to H_2.
Low electronic conductivity	Allows separation of charge between the anode and cathode and prevents cell shorting.	
Thermal stability	The membrane must not lose its chemical or mechanical properties at the >80°C operating temperature of the system	
Mechanical stability	The membrane should be resistant to cracking and pinhole fractures, which would cause cell shorting and ultimately reduce the lifetime of the hydrogen fuel cell.	Mechanical stability is important for membranes used in water electrolysis applications. Large pressure differential across the anode and cathode puts the membrane under particularly high stress.
Chemical durability	Chemical durability is important for membranes used in fuel cells and electrolysers, they are very thin and must be able to operate without degradation. The membrane must be stable to the acidic environment of the cell, as well as resistant to impurities and contaminants.	
Hydrophobicity	Hydrophobicity of the polymer backbone assists in driving water out of the membrane and also reduces effects of swelling upon hydration	
Hydrophilicity	A hydrophilic sidechain structure is important to ensure water is absorbed by the membrane to allow protons to move freely within its structure.	
Sources: Kodama, K., Miura, F., Hasegawa, N., Kawasumi, M., & Morimoto, Y. (2006). Degradation of NafionMembranes in Hydrogen Peroxide. *ECS Meeting Abstracts*, *MA2005-02*(33), 1185. Moreno Ostertag, L., Ling, X., Domke, K. F., Parekh, S. H., & Valtiner, M. (2018). Characterizing the hydrophobic-to-hydrophilic transition of electrolyte structuring in proton exchange membrane mimicking surfaces. *Physical Chemistry Chemical Physics*, *20*(17), 11722–11729.		

6.1.2 Assessment of alternative membranes

6.1.2.1 Hydrocarbon membranes

'Hydrocarbon membrane' is a broad term which is generally used to describe alternative membrane materials which are non-fluorinated. Many of these hydrocarbon membranes do have polymeric backbones containing only carbon and hydrogen atoms, however those containing heteroatoms such as oxygen or nitrogen can still be classified as a hydrocarbon membrane as to demonstrate their non-PFAS structure. In most circumstances, proton conductivity is achieved in a comparable manner to that for Nafion™, where functionalisation of the polymer by the inclusion of sulfonate side chains allows for channels of water to establish in the membrane when hydrated.

The primary potential alternative to Nafion™ membranes in hydrogen fuel cells are phenylene-based hydrocarbon membranes. The use of these membranes in fuel cells and water electrolysers has been researched extensively and presents challenges restricting it from becoming a commercially available alternative for these applications. Its ability to operate in a wider temperature range, cost efficiency, and low environmental impacts are promising developments for the industry[70]. However, even the best hydrocarbon membranes have been shown to have a lifetime of only hundreds or thousands of hours, compared to fluoropolymer membranes which can last tens to hundreds-of-thousands of hours.

A key issue identified for its use as an alternative to Nafion™ is its brittleness when dry and a soft gel like texture when wet. The swelling and gel like texture under wet conditions is due to the less defined separation of hydrophobic and hydrophilic regions resulting in smaller passages for proton conduction[71], requiring the need for polytetrafluoroethylene (PTFE) or hydrophobic material reinforcement to combat these issues. Studies have shown that hydrocarbon MEAs reach the same proton conductivity as Nafion™ membranes only at high humidity and is an area of further research and development. Currently, hydrocarbon membranes cannot achieve the required lifetime durability to be used as commercially viable alternatives to fluoropolymer membranes.

6.1.2.2 Polyether ether ketone (PEEK)

PEEK is a chemically inert thermoplastic polymer consisting of repeating diphenylketone ether units synthesised from 4,4-difluorobenzophenone and bisphenolate salts[72]. PEEK and its composites demonstrate excellent chemical resistance and resistance to biodegradation, which make it suitable for sensitive, high-performance applications in the chemical, aerospace and medicinal industries. More recently, functionalised PEEK has been developed into proton exchange membranes. PEEK is normally formed into a proton exchange membrane by inclusion of sulfonate groups into the polymer structure, and as such, exhibits a similar proton conduction mechanism to Nafion™. Since the non-fluorinated PEEK backbone is not as hydrophobic as the perfluorinated backbone of Nafion™, the polymer is susceptible to weakening upon hydration, compromising its mechanical and chemical stability. Laboratory based tests of PEEK based proton exchange membranes as a part of a MEA have shown lifetimes of only hundreds to low-thousands hours, much lower than the >25,000 hours that is standard for MEAs containing Nafion™ membranes[73].

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70 Nguyen, H., Klose, C., Metzler, L., Vierrath, S., & Breitwieser, M. (2022). Fully Hydrocarbon Membrane Electrode Assemblies for Proton Exchange Membrane Fuel Cells and Electrolyzers: An Engineering Perspective. Advanced Energy Materials, 12(12), 2103559. https://doi.org/10.1002/AENM.202103559

71 https://onlinelibrary.wiley.com/doi/full/10.1002/aenm.202103559 accessed September 2022

72 Iulianelli, A., & Basile, A. (2012). Sulfonated PEEK-based polymers in PEMFC and DMFC applications: A review. International Journal of Hydrogen Energy, 37(20), 15241–15255. https://doi.org/10.1016/J.IJHYDENE.2012.07.063

73 Information obtained with stakeholder consultation

6.1.2.3 *Overall conclusions*

There are many other non-PFAS membrane materials being studied such as hydrocarbon membranes and other sulfonated non-PFAS membranes. These alternatives have mostly been rejected by MEA manufacturers due to insufficient mechanical stability under operating conditions or still require significant R&D before becoming commercially viable. Table 6-2 summarises the key functionality points of the aforementioned potential alternatives and highlights their suitability for use in PEMFCs.

It is evident that Nafion™ membranes offer a unique range of functionality with respect to fuel cells that cannot yet be achieved by non-fluorinated alternatives. If the mechanism of proton conduction of the alternative remains the same as Nafion™ (i.e., through water channels dictated by sulfonate groups) then structural compromise upon exposure of the polymer to water drastically limits the lifetime of the membrane. Research is currently underway to increase the longevity of non-fluorinated membranes, however, there is currently no alternative membrane material which can directly replace Nafion™ or other fluoropolymer membranes in PEMFC or PEMWEs.

Table 6-2: Summary of proposed alternative proton exchange membrane materials for fuel cells

Membrane	Mechanical stability	Chemical stability	Proton conductivity	Comments
Nafion™	Excellent	Good, some sensitivity to CO and H_2O_2	Up to 0.1 Scm^{-1} @ 80°C under humid conditions	Ideal material for both water electrolysis and fuel cell technologies, currently used for PEMFC and PEMWE systems.
Hydrocarbon	Poor, swells when hydrated	Moderate, sensitivity to H_2O_2	>0.1 Scm^{-1} @80°C under humid conditions	Currently in research, promising results but needs structural reinforcement before viable
Sulfonated-PEEK	Poor, swells when hydrated	Moderate, sensitivity to hydrolysis and H_2O_2	Up to 0.08 Scm^{-1} @ 100°C	Commercially unavailable high-performance research polymer, shares the same swelling properties as hydrocarbon membranes

Source documents:
Iulianelli, A., & Basile, A. (2012). Sulfonated PEEK-based polymers in PEMFC and DMFC applications: A review. International Journal of Hydrogen Energy, 37(20), 15241–15255.
Nguyen, H., Klose, C., Metzler, L., Vierrath, S., & Breitwieser, M. (2022). Hydrocarbon Membrane Electrode Assemblies for Proton Exchange Membrane Fuel Cells and Electrolyzers: An Engineering Perspective. Advanced Energy Materials, 12(12), 2103559 https://doi.org/10.1002/aenm.202103559
Modification of Poly(ether ether ketone) Polymer for Fuel Cell Application Shulka et. Al.

6.1.3 Assessment of alternative water electrolyser technologies for hydrogen production

6.1.3.1 *Hydrocarbon membranes for PEMWEs*

Hydrocarbon membrane electrode assemblies used in electrolysers meet the proton conductivity requirements required by the manufacturers of water electrolysers. However, the membranes need to be thicker to meet the durability requirements from the high differential pressure across the cell, and reduction of gas crossover. The use of thick membranes (50-180 µm) results in high protonic resistance and low voltage efficiency[74]. From consultation with downstream users who have undertaken R&D into hydrocarbon membranes for water electrolysis, it is clear that hydrocarbon membranes do not offer a sufficient lifetime to be viable within commercial products. Hydrocarbon membranes which are of sufficient thickness as show suitable operational lifetimes are demonstrate protonic resistance which is too high to be acceptable by water electrolyser manufacturers.As such, hydrocarbon membranes are not currently considered an alternative for this application.

6.1.3.2 Alkaline water electrolysers (AWEs)

Description of the technology

AWEs form hydrogen and oxygen from water by the electrolytic disassociation of water at the cathode, forming hydroxide anions and adsorbed hydrogen atoms on the cathode surface. Adsorbed hydrogen atoms then combine to form hydrogen gas. At the anode, hydroxide ions are oxidised to form oxygen and water. AWEs use an aqueous sodium or potassium hydroxide solution as the electrolyte instead of a solid polymer electrolyte like PEMs. The electrodes are separated by a diaphragm to prevent the recombination of hydrogen and oxygen and to transport hydroxide ions from one electrode to the other (See Figure 6-1). AWEs must operate at isobaric pressure, meaning that the operating pressure at the anode and cathode must be equal, and as a result, hydrogen produced by an AWE system is at atmospheric pressure.

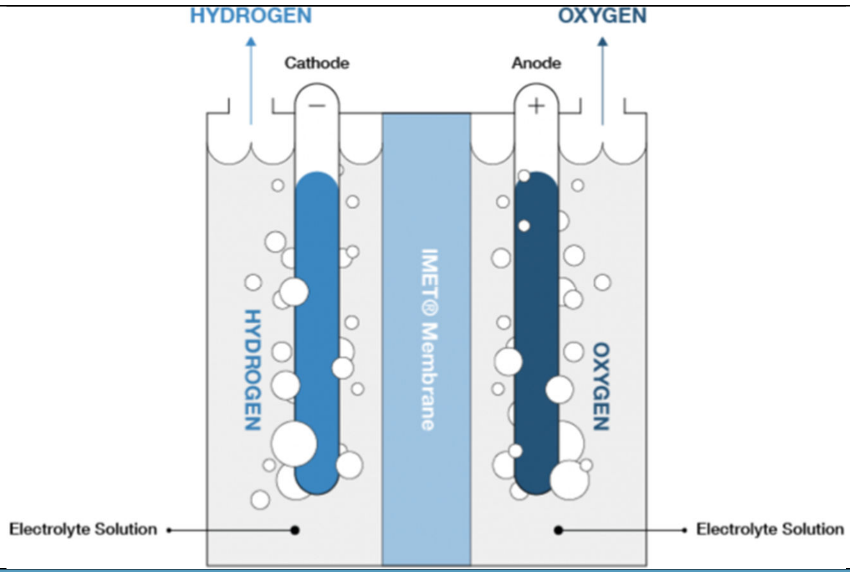

Figure 6-1: Alkaline electrolysis cell
Source: *https://www.cummins.com/new-power/applications/about-hydrogen/electrolysis accessed June 2022*

Performance of the technology

The performance and main characteristics of AWEs are compared to those of PEM electrolysers in table xx.

[74] https://onlinelibrary.wiley.com/doi/full/10.1002/aenm.202103559 accessed September 2022

Table 6-3: Comparison of the performance of AWE and PEM electrolysers		
Property	**AWE electrolysers**	**PEM electrolysers**
Electrolyte	Aqueous KOH or NaOH (20-40 wt%)	Fluoropolymer proton exchange membrane (Nafion™ or other fluorinated membranes)
Cathode catalyst material	Nickel or alloys of nickel and molybdenum	Platinum or Pt-Pd alloys
Anode catalyst material	Nickel or alloys of nickel and cobalt	Precious metal oxides (RuO_2, IrO_2)
Current density (Acm^{-2})	0.2-0.4	0.6-2.0
Cell voltage (V)	1.8-2.4	1.8-2.2
Operating pressure (bar)	1-30	50-80
Hydrogen production rate (Nm^3h^{-1})	<760	<40
Gas purity (vol %)	>99.5	>99.9999
Stack lifetime (h)	60-100k	20-60k
Source:		

Since AWEs are the oldest and most mature water electrolysis technology, their performance has been well-optimised. AWEs are capable of producing large volumes of hydrogen gas and demonstrate excellent stack lifetimes. AWEs make use of relatively cheap materials for both the catalyst and the electrode separator when compared with PEMWEs. However, AWEs cannot produce hydrogen gas under significant pressures, meaning that the hydrogen obtained from AWEs must undergo costly low-pressure storage and compression procedures which can account for three-quarters of hydrogen storage and transport costs, whereas hydrogen produced by PEM electrolysers can pressurise hydrogen *in situ*.

In addition, the hydrogen produced by AWEs is typically of a lower purity than that generated by PEMWEs. For applications where the use of high-purity hydrogen gas is necessary (e.g., in PEM fuel cells), hydrogen produced by AWEs may be unacceptable.

AWEs demonstrate a reduced cell efficiency compared to PEMWEs, typically with a current density four-times lower than that of PEMWEs operating at the same voltage. This reduction in efficiency is due to increased cell resistance associated with the use of less efficient catalysts at the anode and cathode, as well as the gradual corrosion of the electrolyser components in the presence of the caustic electrolyte solution.

AWEs are accompanied with a relatively large Balance of Plant (BoP) compared to PEMWEs which includes alkaline circulation pumps, alkali and water tanks and gas coolers. As a result of this increased BoP, AWEs are typically three-times the size of their PEMWE counterparts.

Current and future use of the technology

AWEs are the most mature electrolyser technology available and have been commercialised for decades. In 2020, the European market for AWEs was €37 million and is predicted to grow with a CAGR of 6.5% between 2021 and 2028. AWEs continue to be an efficient means of green hydrogen production and will contribute to the EU goals for overall hydrogen production in the coming years alongside PEMWEs.

It is important to note that while AWEs do not use fluoropolymers as an essential material to achieve functionality, fluoropolymers can often be used within the balance of plant and aid in the delivery of the functionality over all, and therefore would almost certainly be affected by a PFAS restriction. In addition, the sodium hydroxide electrolyte which is used in AWEs is produced almost exclusively by the chloralkali process as described previously in this report. Nafion™ is an essential material to the chloralkali process, and as such the supply of sodium hydroxide which allows this alternative technology to function would also be affected by restriction of fluoropolymers.

6.1.3.3 Anion exchange membrane (AEM)

Description of the technology

AEM electrolysers are a modern technology which is similar in function to both AWEs and PEMWEs. In an AEM, water is reductively disassociated at the cathode which normally contains non-precious metal catalysts such as nickel and nickel alloys. The disassociation of water leads to the formation of hydroxide anions and surface adsorbed hydrogen atoms. Hydrogen gas can then be formed at the cathode via chemical combination of adsorbed hydrogen atoms, or by a further reductive disassociation of water step.

The hydroxide anions formed at the cathode then migrate across the anion exchange membrane to the anode, where hydroxide is electrocatalytically oxidised to water and oxygen gas by non-precious metal oxide catalysts.

The anion exchange membrane can be comprised of a variety of materials including both fluorinated and non-fluorinated polymers which are doped with cationic functional groups which selectively aid the transport of anionic hydroxide ions.

Performance of the technology

The performance and main characteristics of AEM electrolysers is compared to that of PEM electrolysers in table xx. It is important to note, however, that AEM electrolyser development is at an early stage of research and therefore the figures quoted in this comparison were obtained in laboratory environments and may not apply to the at-scale technology.

Table 6-4: Comparison of the performance of AEM and PEM electrolysers		
Property	**AEM electrolysers**	**PEM electrolysers**
Electrolyte	Anion exchange membrane (can be fluorinated or non-fluorinated)	Fluoropolymer proton exchange membrane (Nafion™ or other fluorinated membranes)
Cathode catalyst material	Nickel or alloys of nickel	Platinum or Pt-Pd alloys
Anode catalyst material	Oxides of nickel, iron or cobalt	Precious metal oxides (RuO_2, IrO_2)
Current density (Acm^{-2})	0.2-1.0	0.6-2.0
Cell voltage (V)	1.8-2.2	1.8-2.2
Operating pressure (bar)	1-30	50-80
Hydrogen production rate (Nm^3h^{-1})	<1	<40
Gas purity (vol %)	>99.99	>99.9999
Stack lifetime (h)	Not yet known*	20-60k
Source: *Laboratory scale prototypes, lifetime depends on the specific membrane and catalysts used		

AEM electrolysers have the potential to produce hydrogen gas of purity comparable to that of PEM electrolysers, and use non-precious metal catalysts to facilitate the electrochemical reaction. However, AEM electrolysers do not yet offer the same high operating pressure or production rate as PEM electrolysers.

AEM electrolysers also show greatly reduced cell efficiencies than PEM electrolysers, where the current density for AEM electrolysers is half the value for PEM electrolysers operating at the same cell voltage – indicating increased cell resistance for AEM electrolysers. This increased resistance is due to the poor diffusion characteristics of the hydroxide anion within the cell.

In addition, the membrane used within the best performing AEM electrolysers within the literature are based on fluoropolymers. Therefore, many AEM electrolyser technologies would fall into the scope of a PFAS restriction. Those AEM electrolysers which do not make use of fluoropolymer membranes also demonstrate reduced stack lifetimes, further limiting their technical feasibility as alternatives to Nafion™ containing PEM electrolysers.

Current and future use of the technology

AEM electrolysers are still in the research stage of development, and as such have not been proven in a commercial setting. AEM electrolyser technology is currently the subject of an EU funded research project as a part of the Horizon Europe scheme. The project known as ANIONE has a €2 million budget and is set to conclude in September 2023. ANIONE aims to validate a fluoropolymer-free 2 kW AEM electrolyser with a hydrogen production rate of 0.4 Nm^3h^{-1} which can operate for a minimum of 2,000 h without a voltage decrease of more than 50 mV. If the research goals are met, then AEM technology would achieve TRL 4 in 2023, however, in order to compete with the performance of commercial PEM electrolysers, significant improvements to production volume and longevity will have to be made without the use of fluoropolymer membranes.

6.1.3.4 Solid oxide water electrolysis

Solid oxide water electrolysers are another class of water electrolyser where H_2O is split into H_2 and O^{2-}. The O^{2-} migrates across the solid oxide electrolyte and is released as O_2 [75]. Solid oxide electrolysers, however, often deteriorate rapidly due to the delamination of the solid electrolyte from the electrode as a result of high oxygen partial pressures causing stresses at the anode[76].

Solid oxide water electrolysers are not yet a mature technology and are currently the focus of multiple EU funded research projects to develop commercially viable technologies. The development of solid oxide water electrolysers is seen as a key aspect of achieving EU hydrogen production policy goals, but it is not yet clear when or to what extent solid oxide technology will be used.

6.1.4 Non-PEM technologies for fuel cells

While there are few alternatives to Nafion™ membranes for use in fuel cells and water electrolysers, there are alternative technologies which accomplish a similar task without the need for PEMs. In this section, a brief overview of these technologies is given, and their role in the hydrogen economy is assessed. It is important to note, however, that while these alternative technologies do not use Nafion™ membranes or dispersions in order to function, it is possible that they make use of fluoropolymer compounds as catalyst binders or support materials and as such may still be impacted by the proposed PFAS restriction.

6.1.4.1 Solid oxide fuel cells (SOFCs)

SOFCs and electrolysers operate in a comparable manner to PEMFCs, where fuel gases are oxidised at the anode and oxygen is reduced at the cathode. However, in a SOFC, the charge carrier is O^{2-} instead of H^+ and the electrolyte is a solid ceramic material which allows migration of the O^{2-} charge carriers (see Figure 6-2). In order to allow the solid electrolyte to conduct O^{2-} at a sufficient rate to produce the required power, SOFCs need to operate at exceedingly high temperatures (500-1000°C). Due to the high operating temperature of the SOFC, expensive platinum group metals are not required at the electrodes, increasing cost efficiency[77]. However, the large weight and thermal shielding requirements of SOFCs has made them so far suitable only for stationary purposes as highly efficient generators, particularly for microgrids such as hospitals and data centres where electrical energy security and consistency is essential. On the other hand, SOFCs are being considered for use as generators in some heavy-duty transport applications such as in commercial aeroplanes[78]. While SOFCs can operate using green hydrogen as the only fuel source, it is more common for them to use natural gas as the fuel, which is run through a reformer to generate a mixture of fuel gases which is comprised of H_2, CO, and CH_4, and the waste products of the SOFC are generally H_2O and CO_2. SOFCs can operate with an electrical efficiency of up to 60%, meaning that much more of the energy stored in the fuel is converted to useful energy as opposed to a classical internal combustion engine generator

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[75] Zheng, Y., Wang, J., Yu, B., Zhang, W., Chen, J., Qiao, J., & Zhang, J. (2017). A review of high temperature co-electrolysis of H2O and CO2 to produce sustainable fuels using solid oxide electrolysis cells (SOECs): advanced materials and technology. Chemical Society Reviews, 46(5), 1427–1463. https://doi.org/10.1039/C6CS00403B

[76] Gazzarri, J. I., & Kesler, O. (2007). Non-destructive delamination detection in solid oxide fuel cells. Journal of Power Sources, 167(2), 430–441. https://doi.org/10.1016/J.JPOWSOUR.2007.02.042

[77] https://www.bloomenergy.com/blog/everything-you-need-to-know-about-solid-oxide-fuel-cells/ accessed September 2022

[78] https://core.ac.uk/download/pdf/11127544.pdf accessed September 2022

which tends to have a maximum efficiency of only 35%. If a SOFC is used in cogeneration applications (where the excess heat is used for heating systems), the overall efficiency can be as high as 80%. This combined heat and power application is particularly useful for commercial and residential applications where both heating and electrical power can be supplied to an area using the same fuel source.

Market data specific to SOFC technology within the EU is limited, however, the global market for SOFCs is estimated to be almost €500 million, and is forecast to grow to €7 billion by 2030 with a high CAGR of 36.5%. This high rate of growth indicates the importance of solid oxide technology in future decarbonisation goals, both within the EU and globally.

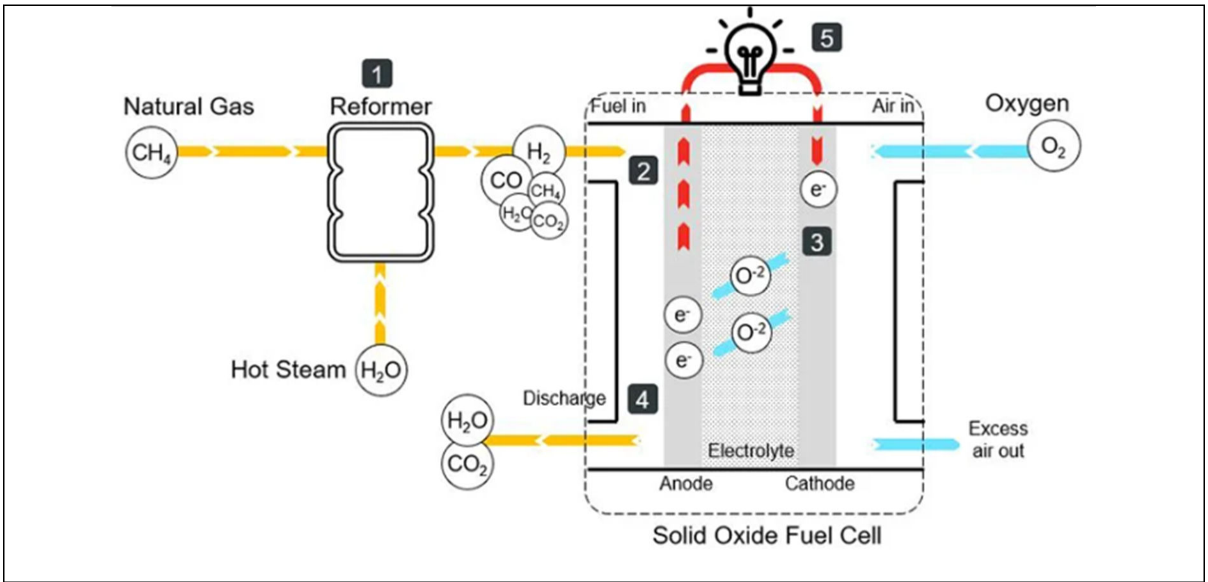

Figure 6-2: Simplified schematic of a solid oxide fuel cell
Source: *https://www.cummins.com/news/2020/05/01/energy-iq-what-solid-oxide-fuel-cell-and-how-fuel-cells-work accessed June 2022*

6.1.4.2 Molten carbonate fuel cells (MCFCs)

MCFCs are another type of high temperature fuel cell, operating at roughly 650°C and normally operate in a comparable way to SOFCs where methane or other gases including hydrogen are used as the input gas, where a mixture of gases is formed and used as the fuel in the MCFC. The fundamental chemistry in an MCFC is different to other types of fuel cell, where CO_2 at the cathode is combined with O_2 and electrons to form CO_3^{2-}, carbonate ions. Simultaneously, CO_3^{2-} at the anode reacts with hydrogen, releasing electrons and forming CO_2 and H_2O (See Figure 6-3)[79]. The anode and cathode are electronically connected by an electrolyte consisting of Na_2CO_3 and K_2CO_3 which is supported by a $LiAlO_2$ matrix. MCFCs offer relatively high efficiencies, however their durability is a concern due to the corrosive nature of the molten carbonate electrolyte. Due to their size and thermal requirements, MCFCs are only used in stationary power generation applications and are not suitable to replace PEMFCs in their primary use in the transport sector. MCFCs do however have interesting potential applications in the decarbonisation of fossil fuel power plants where they can also be used to concentrate CO_2 from flue gases in preparation for carbon capture procedures.

[79] https://fuelcellsworks.com/knowledge/technologies/mcfc/ accessed July 2022

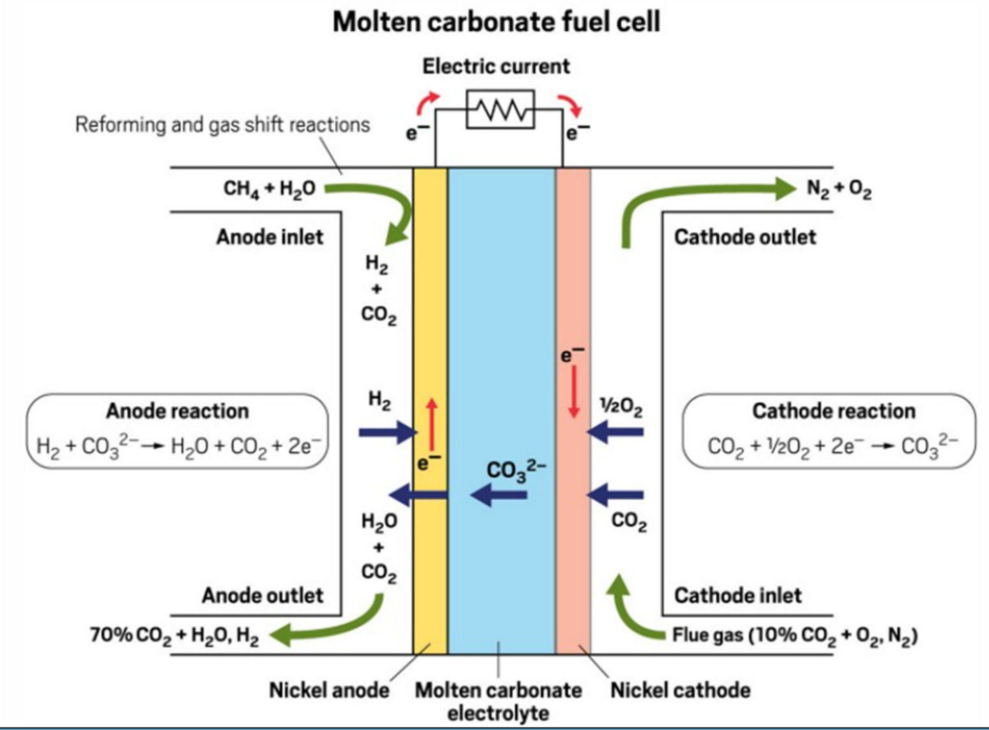

Figure 6-3: Simplified schematic of a molten carbonate fuel cell
https://cen.acs.org/energy/FuelCell-Energys-molten-carbonate-fuel/99/i11 accessed June 2022

EU specific market data for MCFCs is limited, however the future application of MCFCs is demonstrated by a projected global increase in MCFC capacity by over 100 MW by 2025. This growth is supported by the potential application of MCFCs as carbon capture and storage technology, as well as their primary use as stationary power and heat generators.

6.1.4.3 Phosphoric acid fuel cells (PAFCs)

These were among the first commercially viable fuel cells and operate in a similar way to HT-PEMFCs, where the only fundamental difference between the two technologies is the electrolyte. In a PAFC, the electrolyte is highly concentrated phosphoric acid suspended in a porous silicon carbide matrix[80]. At low temperatures, phosphoric acid is a poor ionic conductor, so the PAFC must operate in the 150-200°C temperature range. Unlike SOFCs and MCFCs, PAFCs require expensive precious metal catalysts due to their moderate operating temperature and only reach electrical efficiencies of around 40%. However, if operated in cogeneration applications, PAFCs have extremely high overall efficiencies of up to 85%.

The European market size for PAFCs in 2021 was approximately €9 billion with a CAGR of 19.75%. While the predicted growth of the PAFC market is substantial, it is notable that this market is projected to grow more slowly than other stationary cogeneration fuel cells. In 2018, 92% of global PAFCs were used in combined heat and power applications, whereas less than 5% were used for vehicular applications.

[80] http://www.fuelcell.co.uk/phosphoric-acid-fuel-cells/ accessed September 2022

6.1.4.4 Alkaline fuel cells (AFCs)

AFCs were the first commercially available fuel cells; they were used by NASA to provide power and water to spacecraft[81]. Their mode of operation is almost the direct reverse of its alkaline water electrolyser counterpart, where an aqueous sodium or potassium hydroxide electrolyte is used to transport hydroxide ions across a semi-permeable membrane. One of the benefits of AFC technology is that it does not require precious metal catalysts to enable the electrochemical reaction and can be operated with only cheap nickel catalysts. As with their water electrolyser counterpart, AFCs are limited by their relatively low specific power densities and large footprint compared to compact PEMFCs. Alkaline fuel cells also are poisoned by CO_2 which is present in the air that provides O_2 to the fuel cell. Release of CO_2 into the alkaline electrolyte can result in accumulation of carbonate salts within the cell, which can increase overpotential and reduce lifetime. AFCs currently have application in the military, space, backup power, and transportation sectors. However, AFC market growth is now limited by PEMFC technology, where the absence of CO_2 sensitivity, electrolyte management and issues with electrolyte conductivity are reduced in the case of PEMFCs.

6.1.4.5 High temperature polymer electrolyte membrane fuel cells (HT-PEMFC)

One major roadblock in the use of non-fluorinated polymers as PEMs is the mechanical resistance of the substance when exposed to moisture. Moisture is necessary for proton transport across many PEM materials, namely those containing sulfonate groups, and thus, any PEM material which is not mechanically stable under the operating conditions of high humidity must be eliminated as an unviable alternative. If, however, the proton conducting capacity of the PEM is not dependent on water content, then mechanical compromise upon addition of water may not be as much of an issue.

Polybenzimidazole (PBI) is a class of polymer that is synthesised by condensation between a tetraamine and a dicarboxylic acid such as isophthalic acid, resulting in a polymer network of repeating benzimidazole units[82]. Proton conductivity in PBI is achieved by doping the polymer structure with an acid, normally phosphoric acid, where the mechanism of proton transport acts via a 'proton hopping' type mechanism, rather than conductivity through water channels as is the case in Nafion™ (See Figure 6-3). This different mechanism of proton transport allows the membrane to operate at temperatures up to 200°C, since evaporation of water from the membrane does not inhibit proton conductivity. In addition, humidification of fuel gases is not necessary for the operation of a PBI based membrane unlike Nafion™ and other sulfonated proton exchange membranes which require high fuel gas humidity to achieve proton conductivity.

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[81] https://www.fuelcellstore.com/blog-section/introduction-alkaline-fuel-cells accessed September 2022

[82] Zhou, Z., Zholobko, O., Wu, X. F., Aulich, T., Thakare, J., & Hurley, J. (2020). Polybenzimidazole-Based Polymer Electrolyte Membranes for High-Temperature Fuel Cells: Current Status and Prospects. Energies 2021, Vol. 14, Page 135, 14(1), 135. https://doi.org/10.3390/EN14010135

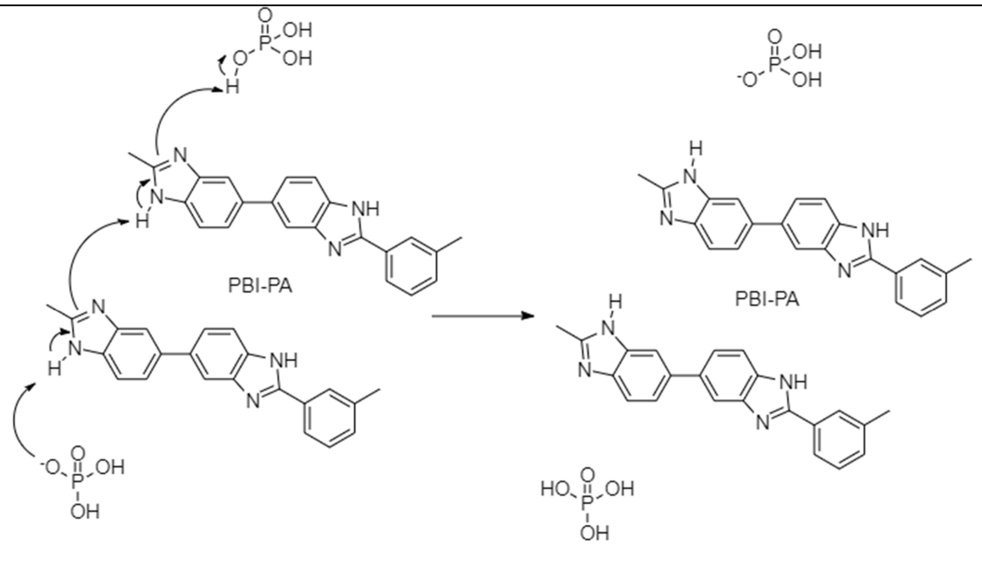

Figure 6-4: Moisture independent proton transfer mechanism in PBI-PA membranes. Simplified PBI structures used for clarity
Source: *https://www.mdpi.com/1996-1073/14/1/135/pdf?version=1609242568 accessed September 2022*

Higher temperatures are required for proton conductivity in PBI membranes (ca. 170°C) and therefore fuel cells which use PBI as the membrane are known as high temperature polymer electrolyte membrane fuel cells (HT-PEMFCs). A HT-PEMFC can be considered as a hybrid between a classical Nafion™-containing low temperature PEM fuel cell (previously discussed as PEMFC but referred to here as LT-PEMFC for comparison purposes) which uses Nafion™ as the membrane, and a phosphoric acid fuel cell. While HT-PEMFCs using PBI membranes have been known and used in a few stationary applications for over 15 years, new developments in engineering solutions have made their use in the transport sector possible, and in some circumstances, preferential to LT-PEMFCs[83]. The high operating temperature of HT-PEMFCs means that large, heavy cooling systems can be avoided which is able to make vast weight savings compared to LT-PEMFCs in some applications[84]. One example of an application where HT-PEMFCs are preferential over LT-PEMFCs is in the aviation industry. HyPoint have designed aircraft engines based on HT-PEMFC technology which can be cooled by air from the atmosphere instead of by liquid coolant. The weight saved from removing the heavy liquid cooling system allows the fuel cells to access specific power and energy densities required by air transport which cannot be achieved by LT-PEMFC systems[85].

The use of PBI membranes does offer significant challenges the largest of which is the leaching of phosphoric acid from the membrane. This leaching issue is amplified by the formation of water at the cathode of the fuel cell, which is able to enhance corrosion. HT-PEMFCs are currently not a market proven technology, with only a handful of examples of prototype systems developed. However, due to their potential to have increased power density and high resistance to impure fuels, HT-PEMFCs

83 Berber, M. R., Fujigaya, T., Sasaki, K., & Nakashima, N. (2013). Remarkably Durable High Temperature Polymer Electrolyte Fuel Cell Based on Poly(vinylphosphonic acid)-doped Polybenzimidazole. https://doi.org/10.1038/srep01764

84 Zhang, J., Aili, D., Lu, S., Li, Q., & Jiang, S. P. (2020). Advancement toward Polymer Electrolyte Membrane Fuel Cells at Elevated Temperatures. Research, 2020, 1–15. https://doi.org/10.34133/2020/9089405

85 Hypoint white paper, found at hypoint.com accessed July 2022

have been identified as a crucial future development in achieving EU decarbonisation goals, both within stationary power and transport sectors.

6.1.4.6 Overall conclusions

The alternative non-PEM fuel cell technologies discussed in this section are summarised in Table 6-5.

Table 6-5: Comparison summary of fuel cell technologies

Technology	Operating temperature	Typical stack size	Efficiency	Pros	Cons
HT-PEMFC	<120°C		60%	Very quick start-up times High energy and power densities Compact and suitable for transport applications High efficiency	Requires expensive Pt catalysts Requires high fuel gas purity Additional balance of plant required for cooling/humidity management
SOFC	500-1000°C	1 kW-2 MW	60%	Does not require expensive catalysis Does not require fluoropolymer membranes	Very long start up times Requires significant thermal shielding Only suitable for stationary applications
MCFC	600-700°C	300 kW- 3 MW	50%	High efficiency (c.a. 65%) Do not require expensive catalysts Does not require fluoropolymer membrane	Low durability due to corrosive electrolyte Only suitable for stationary applications
PAFC	150-200°C	5-400 kW	40%	Highly resistant to impurities Does not require fluoropolymer membrane	Requires Pt catalyst Low specific power density Heavy for its power output
AFC	<100°C	1-100 kW	60%	High performance due to good kinetics High efficiency	Susceptible to CO_2 poisoning Poor membrane durability Corrosion concerns
HT-PEMFC	150-200°C	10-100 kW	50%	Reduced cooling and fuel gas humidification requirements compared to LT-PEMFCs High tolerance to CO and methanol, can use 'dirty' hydrogen as the fuel source Stable membrane with long lifetime	Longer start-up times Lower overall efficiency Requires higher catalyst loading than LT-PEMFC

The alternative fuel cell technologies summarised above, while applicable in some conditions, often show significant drawbacks that limit their applications, particularly in the automotive industry where the low operating temperature, high efficiency, and high specific power density of PEMFCs is of vital importance to the application of fuel cells in vehicles. With regards to alternative technologies which could universally replace PEMFCs in their primary role within the transport sector, there currently are no viable alternatives.

In the case of the transport sector, the alternative technology to LT-PEMFC, the HT-PEMFC is still in its commercial infancy and requires further development of the technology before the alternative is economically and technically feasible. Even when HT-PEMFC technology matures, it will not replace LT-PEMFC technology in all applications due to its longer start-up times and higher catalyst loadings and fundamental limitations in efficiency.

It is also important to note that while none of the alternatives make use of Nafion™ products, it is a high possibility they do use fluoropolymers in the ancillary equipment of the FC or WE technology. The chemical and mechanical stability of fluoropolymers such as PTFE, PVDF and FEP make them ideal materials for long-life tubing, gaskets and binders and may be used in any of these alternative technologies.

LT-PEMFCs still offer unparalleled efficiency, longevity and power output for their compact size and while there are some applications where HT-PEMFCs may be substituted or even preferred such as some semi-trucks and air propulsion systems, this technology has large limitations and will not be able to replace LT-PEMFCs in their primary role within the fuel cell landscape.

6.1.5 Commercial Availability

Alternatives for Fuel Cells

Many of the alternative stationary fuel cell technologies to PEMFCs discussed in the previous section are well established and are commercially available. SOFCs in particular are widely manufactured and used in the stationary power sector. MCFCs are also widely used in stationary combined heat and power applications and have seen a growth in interest for supplementary use in fossil fuel power plants due to their ability to concentrate the level of CO_2 in flue gas, making it suitable for CO_2 capture[86].

The alternative hydrocarbon membrane materials discussed in the previous section are still in early research stages and based on their poor lifetime performance it is difficult to envisage a situation where hydrocarbon alternatives to Nafion™ would be widely available in the foreseeable future.

The material which is sufficiently stable over its lifetime is PBI for use in HT-PEMFCs, this material is commercially available but is only produced in small quantities (hundreds of m^2 per year, density not known) and is applicable to some of the transport sector uses which are currently fulfilled by Nafion™.

Alternatives for water electrolysis

Alongside PEMWE technology, alkaline water electrolysis is currently one of the most used methods of producing green hydrogen. Alkaline water electrolysis (AWE) does not use Nafion™ or other fluoropolymers as a membrane material, and therefore at a first glance appears to be immune from a

[86] https://cen.acs.org/energy/FuelCell-Energys-molten-carbonate-fuel/99/i11 accessed September 2022

potential PFAS restriction. However, AWEs can often use other fluoropolymers such as Teflon or fluoroelastomers within their ancillary equipment in order to achieve required production volumes and lifetimes. The AWE market would undoubtably be strained in the event of a fluoropolymer restriction and therefore EU policy goals relating to the production of green hydrogen in the coming years would not be met. In addition, the manufacturing process responsible for providing the caustic electrolyte used in AWEs also uses Nafion™ as a key component. The potential shortage of electrolyte following a fluoropolymer restriction would further subtract from the green hydrogen production capacity in the coming years.

6.1.6 Hazard and risk of not in-kind alternative substances

While alternative membrane materials are normally non-hazardous due to their large molecular weight, their monomers and other reagents used in their synthesis may be classed as hazardous materials. This is an important consideration for upstream manufacturers of any alternative materials since their hazard classification will affect their manufacturing processes and precautions.

PBI membranes, like fluoropolymers, are intrinsically non-hazardous, however the precursor tetraamines are often classed as carcinogenic and the processing solvent NMP is subject to authorisation under REACH. In addition, the dopant phosphoric acid is highly corrosive, and the solvents used to deposit the membrane may have adverse effects to the environment and to human health. Table 6-6 summarises some common chemicals used in the manufacture of PBI membranes and their hazards. In addition, PBI membranes also are able to release decomposition products upon excessive heating, however unlike fluoropolymers, PBI membranes only emit relatively non-toxic gases such as H_2O, CO_2 and CO depending on the availability of oxygen.

Table 6-6: Hazard properties of chemicals involved in the manufacture of PBI membranes

Compound	Description	Classification according to (EC) No 1272/2008
3,3'-Diaminobenzidine (CAS: 91-95-2)	Tetraamine used as a monomer for PBI membranes	H302 Acute toxicity, Oral (Cat. 4) H319 Eye irritation (Cat. 2) H341 Germ cell mutagenicity (Cat. 2) H350 Carcinogenicity (Cat 1B)
Phosphoric acid (CAS: 7664-38-2)	Common acidic dopant	H290 Corrosive to Metals (Cat. 1) H302 Acute toxicity, Oral (Cat. 4) H314 Skin corrosion (Sub-Cat. 1B) H318 Serious eye damage (Cat. 1)
N-methyl-2-pyrrolidone (NMP) (CAS: 872-50-4)	Common solvent for PBI processing	H315 Skin irritation (Cat. 2) H319 Eye irritation (Cat. 2) H360D Reproductive toxicity (Cat 1B) H335 Specific target organ toxicity - single exposure (Cat. 3), Respiratory system
Source documents: Sigma-Aldrich material safety data sheets		

Since PEM technology, particularly water electrolysers, can operate under high differential pressures there is a particularly considerable risk of membrane rupture if the alternative material is not sufficiently mechanically stable to maintain these pressures. The gases involved with water electrolysis, H_2 and O_2 are highly explosive when mixed and therefore if the membrane fails under these high pressures, there could be extremely hazardous consequences from the subsequent formation of explosive mixtures of the two gases.

6.1.7 Economic cost

Due to the relatively recent commercialisation of PBI membrane fuel cell technology, this alternative material is currently extremely costly in comparison to the well-established Nafion™ supply lines. This combined with the immaturity and lack of universal applicability of the HT-PEMFC technology itself means that implementing PBI membranes as an alternative material to Nafion™ is not economically feasible.

Since there are currently no direct alternatives to Nafion™ membranes which are technically feasible, assessment of the economic cost of replacing Nafion™ for PEMFCs or water electrolysers is not possible.

6.1.8 Conclusions

Despite many research efforts in recent years on not in-kind alternatives, Nafion™ still remains the material of choice for PEMFCs due mostly to its unique mechanical and chemical stability under the humid operating conditions of fuel cells and water electrolysers. While the proton conducting properties of Nafion™ have been replicated by sulfonated hydrocarbon and PEEK membranes, the longevity of these alternative materials has so far ruled out their utility in commercial products.

There is some potential to replace Nafion™ for fuel cells in some of its transport sector applications with HT-PEMFC technology, which uses a non-fluorinated PBI membrane, for which its intrinsically lower power output can be balanced out by its reduced need for heavy water management and liquid cooling systems. However, the applications in which HT-PEMFC technology can replace LT-PEMFC technologies are niche and in their infancy within the fuel cell landscape.

For the production of hydrogen gas via electrolysis of water, there do exist some technologies which accomplish the same task without the use of Nafion™ membranes. SOWEs and AWE technologies in particular are able to generate hydrogen from water with reasonable power efficiency, however they take up orders of magnitude more space and do not show the same longevity as PEMWEs due to delamination of the electrolyte from the anode in the case of SOWEs and corrosion in the case of AWEs.

For stationary power systems, there are multiple alternative technologies which do not use polymer electrolyte membranes such as SOFCs, MCFCs, PAFCs and AFCs. These technologies are well established and already account for a substantial portion of the overall fuel cell market. All of these alternative technologies are extremely large and heavy for their power output, making their potential to replace the compact and efficient LT-PEMFC within the transport sector extremely limited.

Overall, all of the alternative fuel cell and electrolyser technologies discussed in this report will all contribute to an extent towards achieving EU decarbonisation policy goals such as REPowerEU and the Clean Hydrogen programme. Without the use of Nafion™ and other similar fluoropolymer membranes, the use of PEMFCs and PEMWEs will discontinue, as there is no suitable alternative. The decarbonisation goals set by the EU took into account the rapidly advancing projections for PEM technology, and therefore if this technology is removed from use, these goal will undoubtably be unachievable.

7 Continued use scenario

7.1 Introduction

This section sets out the continued use (or baseline) scenario for the Advanced Performance Materials (APM) division of Chemours and its downstream users in relation to the manufacture, export, import, sale, and use of fluoropolymers. The scenario assumes that APM will be able to import, manufacture, place on the market and use these substances without any restriction. It also assumes that all downstream users will be able to purchase and use fluoropolymer products offered by APM and these same downstream users will be able to manufacture finished articles that are either partly or wholly composed of fluoropolymers or use fluoropolymers during their respective manufacturing processes.

The continued use scenario will focus on the current import of the products Nafion™ IXM membranes which are comprised of perfluoro sulfonic acid alkeneionomer and polytetrafluoroethylene (PTFE) copolymers as explained in section 2. Specifically, this socio-economic analysis will focus on the import of Nafion™ IXM membranes for use in water electrolysis equipment and heavy-duty hydrogen fuel cells for use in heavy duty hydrogen fuel cell vehicles (see previous sections 2 and 4).

References and extrapolations to other applications within the hydrogen economy market are also made at a higher level with a mix of quantitative and qualitative assessment with regards to European strategic goals and environmental factors such as greenhouse gas emissions. Chemours already holds a strong position in the supply chain of these products within Europe, meaning they possess significant market share. These markets are expected to adapt and change significantly in order to grow in response to global pressures driving the hydrogen economy, but APM intend to retain their market capitalisation. Alongside use specific information for APM this section will also present wider market and supply chain information for the various players and sectors for the above stated uses of Chemours APMs products.

7.2 Imports and profits

This section presents various economic indicators for Chemours APM business division. The indicators discussed are the import tonnes of Nafion™ IXM membranes, the size of these import markets in terms of the revenue earned from their import and the profits generated from the sale of these materials for the uses described above. The RPA study team has extrapolated data by using reported 2021 import and sales data from Chemours APM to predict the import, sales, and profits of the business division up to and including the end of 2035. The data has been extracted from surveys created by RPA and answered by Chemours APM. The RPA study team has presented tonnage, value, and profit figures from 2021-2035 to demonstrate how each market will develop between now and the possible start of a restriction. However, only the figures from 2026-2035 are considered and discussed within the analysis of the continued use scenario. The assessment period being employed for this continued use scenario is from 2026-2035, which considers the expected time the restriction will be in place as well as a phase-out period. The timeline will be in the non-use scenario, as discussed in more detail in section 8. This assessment period (ten years) reflects the expected timeframe for alternatives and new chemicals to be developed in the event that a PFAS Restriction will come into force and fluoropolymers can no longer be utilised. A more detailed explanation for the reasoning behind the 2026-2035 timeframe is provided in section 8.1. It should be noted that the following report sections will refer to Chemours Nafion™ product names and not the chemical substances used to create them.

7.2.1 Nafion™ IXM membrane imports and profits

Chemours APM produce and supply Nafion™ IXM for various end use markets throughout Europe which are discussed in more detail in section 7.4. This material acts as an ion exchange membrane for various industrial based uses, but it has particular importance within the hydrogen economy which is the focus of this SEA and the role of the hydrogen economy in European strategic goals is discussed throughout but focussed on in section 8.9. Table shows the total amount of Nafion™ IXM which will be imported into the EU27/EEA by Chemours APM each year between 2021 and 2035 (Grand total), and presents the total amount relevant for the selected assessment period (Assessment period total), i.e. 2026-2035. All numbers throughout the report have been rounded. It should be noted that Nafion™ IXM is imported as articles (rolls of material) and is generally reported in terms of m^2 of material however to maintain comparability between uses and applications within this report Chemours APM and RPA have converted these m^2 import values into equivalent tonnage weights of the Nafion™ IXM fluoropolymer material being imported.

Table 7-1: Total tonnes of Nafion™ IXM membranes imported into the EU27/EEA		
Year	**Lower bound**	**Upper bound**
2021	16	18
2022	18	20
2023	20	23
2024	24	28
2025	28	34
2026	36	44
2027	46	58
2028	61	78
2029	84	108
2030	117	153
2031	167	218
2032	240	316
2033	347	459
2034	507	672
2035	743	987
Assessment period total	2,348	3,093
Grand total	2,454	3,217
Source: RPA study team analysis		

Over the course of the assessment period a total of 2,348 to 3,093 tonnes of Nafion™ IXM will be supplied by Chemours APM for use by downstream users in Europe. As mentioned above one of the important and rapidly growing uses of Nafion™ IXM is its use within the hydrogen economy. The hydrogen economy is comprised of two sectors, the hydrogen generation industry, and the fuel cell market. The purpose of these two industries within the hydrogen economy is to generate and supply hydrogen and supply the equipment within which said hydrogen can be used to generate energy. The hydrogen generation market is currently going through a transitionary phase whereby it is moving away from the current method of generating hydrogen by steam reformation of methane to instead utilising larger scale water electrolysis equipment. Overall, the hydrogen economy is currently a small portion of the total Nafion™ IXM sales made by Chemours APM but will become dominant given the importance of this sector in helping the EU achieving its ambitious environmental targets it is set to see substantial growth between now and 2035. Table provides the split between tonnes of Nafion™ IXM which are imported for use within the hydrogen economy and the tonnes imported for other uses.

Table 7-2: Tonnes of Nafion™ IXM membranes imported by use				
	Hydrogen economy use		Other uses	
Year	Lower bound	Upper bound	Lower bound	Upper bound
2021	3	4	13	14
2022	4	6	13	14
2023	7	9	14	15
2024	10	13	14	15
2025	14	19	14	15
2026	21	28	14	16
2027	32	42	15	16
2028	47	62	15	16
2029	69	92	15	16
2030	102	136	15	16
2031	152	202	15	16
2032	224	299	15	16
2033	332	443	15	17
2034	491	655	16	17
2035	728	970	16	17
Assessment period total	2,198	2,931	150	162
Grand total	2,236	2,982	218	235
Source: RPA study team analysis				

As seen above the hydrogen economy is set for a substantial level of sustained growth over the years prior to a potential restriction and years during the assessment period. This high growth is driven by both components of the hydrogen economy, water electrolysis equipment and fuel cells, seeing rapid expansions of their capacity as the market embraces the technology as a greener future for energy generation. The imports of Nafion™ IXM for use in the manufacture of water electrolysis equipment is set to increase by 48% per year over the course of the above timeline from 2021-2035 and the imports for use in fuel cells are set to increase annually by 54% demonstrating how primed this industry is for rapid expansion to meet green energy demands.

The drive in the demand for water electrolysis equipment as previously mentioned is in part due to the hydrogen and energy generation industries transition away from current technology to this greener alternative requiring more large-scale industrial manufacture of affordable hydrogen through water electrolysis. The second driver of this demand increase is the wider move towards more secure energy sources in the wake of international crises in eastern Europe. A renewed push to move away from reliance on gas and natural resources supplied by other countries is fuelling demand for energy which can safely and securely generated within a member states' or within the EUs borders. Hydrogen power is a potential solution and aide to this transition to energy security with hydrogen production and energy generation from hydrogen being possible at a national level with the correct investment and infrastructure being implemented.

The demand for fuel cells is being driven by two factors. The first is the increase in hydrogen production requires additional fuel cell sources to convert this hydrogen into energy. Not all fuel cells require a Nafion™ IXM membrane as some on the market do currently use other technologies but given the efficiency and longevity of fuel cells that use Nafion™ IXM is being realised within the market demand for PFAS based products is rapidly increasing and changing the market landscape. The second driver of demand for hydrogen fuel cells is the transition away from internal combustion engines. While Li-ion battery powered electric vehicles are becoming the preferred product of choice for light duty, low-range vehicles, larger heavier duty vehicles are suffering from poor ranges when using Li-ion batteries. A solution to this problem is the development of heavy-duty, long range goods vehicles which use heavy-duty fuel cells as their power source, therefore with internal combustion engines set to be phased out by 2035 portions of the automotive market will be looking to transition to fuel cells thus driving demand for the product.[87] This will likely increase the demand particularly for Nafion™ IXM based fuel cells due to their efficiency and the length of time they are able to operate before requiring replacement or experiencing a substantial loss in performance. Table presents the split between Nafion™ IXM which is imported for use in water electrolysis equipment and that which is predicted to be imported for use in fuel cells.

Table 7-3: Tonnes of Nafion™ IXM membranes imported by hydrogen economy use

Year	Water electrolysis equipment		Fuel cells	
	Lower bound	Upper bound	Lower bound	Upper bound
2021	3.0	4.0	0.0	<0.1
2022	4.4	5.9	0.0	<0.1
2023	6.5	8.7	0.0	<0.1
2024	9.7	12.9	0.0	0.1
2025	14.3	19.1	0.1	0.1
2026	21.2	28.3	0.1	0.1
2027	31.4	41.9	0.1	0.2
2028	46.5	62.0	0.2	0.3
2029	68.8	91.7	0.3	0.5
2030	101.9	135.8	0.5	0.7
2031	150.8	200.9	0.8	1.1
2032	223.1	297.4	1.2	1.7
2033	330.2	440.1	1.8	2.7
2034	488.7	651.4	2.7	4.1
2035	723.3	964.0	4.2	6.3
Assessment period total	2,186	2,913	12	18
Grand total	2,224	2,964	12	18

Source: RPA study team analysis

The primary strategic focus of Chemours APM will be to develop sales within the water electrolysis equipment space. This is because the infrastructure for energy production using clean hydrogen is in greater need of Nafion™ IXM membranes at present. Therefore, while fuel cell applications of Nafion™ IXM will grow rapidly they will remain small compared to water electrolysis equipment applications, but due to the reasons stated above even these conservative quantities of Nafion™ IXM set to be imported will form a vital pillar in the supply chain of a product which will be pivotal in the achievement of European environmental goals under the Green Deal.

Like many specialist fluoropolymer products Nafion™ IXM is a high value material due to its availability and patented status with its selling price within Europe being between €1.5 and €2 million per tonne of material. Using this selling price and the above stated tonnages the RPA study team has estimated the size and value of the market which Chemours APM is supplying within Europe. Table presents the combined value of the Nafion™ IXM market for both hydrogen economy and other use applications. These figures have been calculated by multiplying the 2021 tonnage values by the above stated sale prices of Nafion™ IXM and then from 2021 to 2035 these values were grown using a 30% compounding rate which is estimated to the be the revenue increase Chemours APM will experience.

[87] https://www.euronews.com/next/2022/06/09/eu-parliament-backs-ban-on-new-petrol-and-diesel-combustion-engine-cars-from-2035 accessed September 2022

After conducting this extrapolation all values were then discounted at the 4% ECHA rate to arrive at and display present values and the below values have also all been rounded to three significant figures. This rounding in some instances causes a slight discrepancy between the individual row values and the value within the grand total and assessment period total but this discrepancy is minimal.

Table 7-4: Total revenue from the sale of Nafion™ IXM membrane imports		
Year	**Lower bound (€)**	**Upper bound (€)**
2021	24,850,000	36,900,000
2022	25,610,000	38,400,000
2023	26,670,000	40,400,000
2024	28,080,000	43,100,000
2025	30,000,000	46,600,000
2026	32,500,000	51,000,000
2027	35,500,000	56,600,000
2028	39,400,000	63,700,000
2029	44,400,000	72,800,000
2030	50,900,000	84,300,000
2031	59,100,000	98,900,000
2032	69,400,000	117,300,000
2033	82,600,000	140,200,000
2034	99,100,000	169,600,000
2035	120,100,000	206,000,000
Assessment period total	633,000,000	1,060,400,000
Grand total	768,210,000	1,265,800,000
Source: RPA study team analysis		

As seen from the table above, over the course of the assessment period Chemours APM are estimated to generate between €633 million and €1.1 billion in total in revenue from the sale of Nafion™ IXM for all uses. Table provides the market value split between the hydrogen economy and other uses of Nafion™ IXM based on the same calculation methodology outlined above.

Table 7-5: Revenue from the sale of Nafion™ IXM membranes by use				
	Hydrogen economy use		**Other uses**	
Year	**Lower bound (€)**	**Upper bound (€)**	**Lower bound (€)**	**Upper bound (€)**
2021	4,650,000	8,200,000	20,200,000	28,700,000
2022	5,810,000	10,300,000	19,800,000	28,100,000
2023	7,270,000	12,800,000	19,400,000	27,600,000
2024	9,080,000	16,000,000	19,000,000	27,100,000
2025	11,400,000	20,000,000	18,600,000	26,600,000
2026	14,200,000	25,000,000	18,300,000	26,000,000
2027	17,700,000	31,300,000	17,800,000	25,300,000
2028	22,200,000	39,100,000	17,200,000	24,600,000
2029	27,700,000	48,900,000	16,700,000	23,900,000
2030	34,600,000	61,100,000	16,300,000	23,200,000
2031	43,300,000	76,400,000	15,800,000	22,500,000
2032	54,100,000	95,500,000	15,300,000	21,800,000
2033	67,700,000	119,000,000	14,900,000	21,200,000
2034	84,600,000	149,000,000	14,500,000	20,600,000
2035	106,000,000	186,000,000	14,100,000	20,000,000
Assessment period total	472,100,000	831,300,000	160,900,000	229,100,000
Grand total	510,310,000	898,600,000	257,900,000	367,200,000
Source: RPA study team analysis				

Despite being a small initial proportion of the total usage of Nafion™ IXM the high value of the fluoropolymer, means the total value of the Nafion™ IXM market within Europe over the course of the assessment period is between €472 and €832 million. In addition to this Chemours APM are estimated to generate between €160 and €230 million additional revenue from sales of Nafion™ IXM for other uses outside of the hydrogen economy.

The value of the hydrogen economy market is also driven primarily by the sale of Nafion™ IXM for water electrolysis equipment as is to be expected given the large difference in tonnages supplied to each application within the hydrogen economy. Table presents the split between value of the fuel cell and water electrolysis equipment import market for Nafion™ IXM. The value presented for the fuel cell market could be a substantial underestimation. This is because, as discussed earlier, the properties of Nafion™ IXM based fuel cells make them an efficient and long-lasting product. This ultimately makes fuel cells produced using this fluoropolymer to be a cost-effective product which could result in more of the heavy duty vehicle (HDV) market moving towards this low carbon solution than has been anticipated and as such the presented estimations within this analysis are on a highly conservative basis of uptake for Nafion™ IXM fuel cells.

Table 7-6: Revenue from the sale of Nafion™ IXM membranes by hydrogen economy use

	Water electrolysis equipment		Fuel cells	
Year	Lower bound (€)	Upper bound (€)	Lower bound (€)	Upper bound (€)
2021	4,630,000	8,170,000	15,500	30,800
2022	5,790,000	10,200,000	19,400	38,400
2023	7,240,000	12,800,000	24,200	48,000
2024	9,050,000	16,000,000	30,300	60,100
2025	11,300,000	19,900,000	37,800	75,100
2026	14,100,000	24,900,000	47,300	93,800
2027	17,700,000	31,200,000	59,100	117,000
2028	22,100,000	39,000,000	73,900	147,000
2029	27,600,000	48,700,000	92,400	183,000
2030	34,500,000	60,900,000	115,000	229,000
2031	43,200,000	76,100,000	144,000	286,000
2032	54,000,000	95,100,000	180,000	358,000
2033	67,400,000	119,000,000	226,000	447,000
2034	84,300,000	149,000,000	282,000	559,000
2035	105,000,000	186,000,000	352,000	699,000
Assessment period total	469,900,000	829,900,000	1,571,700	3,118,800
Grand total	507,910,000	896,970,000	1,698,900	3,371,200

Source: RPA study team analysis

The true value of the Nafion™ IXM market which is realised and returned to the European economy does not come from the revenue-based market valuation or the revenue generated itself but instead from the profits which are earned on these revenues. Nafion™ IXM sold by Chemours APM has a substantial profit margin on its sales because of the efficiencies, capital investments and proprietary nature of the product. This margin is also set to increase from 2021 to 2025 as additional economies of scale are experienced as production of Nafion™ IXM is increased to meet rising demand. The exact profit margins used across the assessment period cannot be disclosed for reasons of confidentiality. Table presents the total profits on all sales of Nafion™ IXM based on the profit margin for sales related to the hydrogen economy and sales for other uses of Nafion™ IXM. The figures below have also been discounted at the 4% rate to arrive at present values and the figures have again been rounded to three significant figures with the two values added together, resulting in some vales not appearing to be rounded to three significant figures.

Table 7-7: Total profits from the sale of Nafion™ IXM membrane imports		
Year	**Lower bound (€)**	**Upper bound (€)**
2021	18,330,000	27,240,000
2022	19,290,000	28,930,000
2023	20,610,000	31,190,000
2024	22,170,000	34,000,000
2025	24,270,000	37,600,000
2026	26,800,000	42,100,000
2027	29,300,000	46,700,000
2028	32,500,000	52,600,000
2029	36,700,000	60,000,000
2030	42,000,000	69,500,000
2031	48,700,000	81,600,000
2032	57,400,000	96,800,000
2033	68,100,000	115,900,000
2034	81,700,000	140,000,000
2035	98,800,000	170,500,000
Assessment period total	522,000,000	875,700,000
Grand total	626,670,000	1,034,660,000
Source: RPA study team analysis		

Over the course of the assessment period Chemours APM from the sale of Nafion™ IXM are estimated to generate between €522 and €876 million in profit. Table andTable provide the hydrogen economy and other uses profit split as well as the split between water electrolysis equipment and fuel cell applications.

Table 7-8: Profits from the sale of Nafion™ IXM membranes by use				
	Hydrogen economy use		**Other uses**	
Year	**Lower bound (€)**	**Upper bound (€)**	**Lower bound (€)**	**Upper bound (€)**
2021	3,430,000	6,040,000	14,900,000	21,200,000
2022	4,390,000	7,730,000	14,900,000	21,200,000
2023	5,610,000	9,890,000	15,000,000	21,300,000
2024	7,170,000	12,600,000	15,000,000	21,400,000
2025	9,170,000	16,200,000	15,100,000	21,400,000
2026	11,700,000	20,600,000	15,100,000	21,500,000
2027	14,600,000	25,800,000	14,700,000	20,900,000
2028	18,300,000	32,300,000	14,200,000	20,300,000
2029	22,900,000	40,300,000	13,800,000	19,700,000
2030	28,600,000	50,400,000	13,400,000	19,100,000
2031	35,700,000	63,000,000	13,000,000	18,600,000
2032	44,700,000	78,800,000	12,700,000	18,000,000
2033	55,800,000	98,400,000	12,300,000	17,500,000
2034	69,800,000	123,000,000	11,900,000	17,000,000
2035	87,200,000	154,000,000	11,600,000	16,500,000
Assessment period total	389,300,000	686,600,000	132,700,000	189,100,000
Grand total	419,070,000	739,060,000	207,600,000	295,600,000
Source: RPA study team analysis				

Table 7-9: Profits from the sale of Nafion™ IXM membranes by hydrogen economy use				
	Water electrolysis equipment		Fuel cells	
Year	Lower bound (€)	Upper bound (€)	Lower bound (€)	Upper bound (€)
2021	3,420,000	6,020,000	11,400	22,700
2022	4,370,000	7,710,000	14,600	29,000
2023	5,590,000	9,860,000	18,700	37,100
2024	7,150,000	12,600,000	23,900	47,400
2025	9,140,000	16,100,000	30,600	60,600
2026	11,700,000	20,600,000	39,000	77,400
2027	14,600,000	25,700,000	48,800	96,800
2028	18,200,000	32,100,000	61,000	121,000
2029	22,800,000	40,200,000	76,200	151,000
2030	28,500,000	50,200,000	95,300	189,000
2031	35,600,000	62,800,000	119,000	236,000
2032	44,500,000	78,500,000	149,000	295,000
2033	55,600,000	98,100,000	186,000	369,000
2034	69,500,000	123,000,000	233,000	461,000
2035	86,900,000	153,000,000	291,000	577,000
Assessment period total	387,900,000	684,200,000	1,298,300	2,573,200
Grand total	417,570,000	736,490,000	1,397,500	2,770,000
Source: RPA study team analysis				

Over the course of the assessment period the sale of Nafion™ IXM membranes for use within the hydrogen economy will return profits between €389 and €687 million with an overwhelming majority of this profit being provided by the sale of Nafion™ IXM for water electrolysis equipment. In addition to this between €132 and €190 million in profits from sales of Nafion™ IXM for other uses. Again, there is the possibility for these estimates to be slightly undervalued given that the markets they are supplying are going through growth periods which are highly unpredictable. Overall, however it is evident that the supply and sale of Nafion™ IXM within Europe is a highly profitable and valuable market which is providing substantial levels of foreign investment through R&D which will be discussed in more detail later but also through the profits being returned to the economy.

7.2.2 Nafion™ IXM dispersions imports and profits

In addition to ion exchange membranes Nafion™ fluoropolymer is also used to produce Nafion™ IXM dispersions which are used to bind the catalyst material to the membrane, allowing for proper transport of protons to the catalyst material across the membrane. This material is only used within the hydrogen economy and as such the following tables within this section only refer to the total hydrogen economy uses and the breakdown between usage in water electrolysis equipment and fuel cells. Like Nafion™ IXM membranes Nafion™ IXM dispersions are not typically recorded in terms of tonnes but instead in litres however the RPA study team and Chemours APM have worked to convert these measurements into tonnes to maintain comparability across products. Table is the total tonnes of Nafion™ IXM dispersions which are estimated to be imported into the EU27. This growth pattern has been estimated based on the average growth rate between fuel cell and water electrolysis equipment sales growth for Nafion™ IXM membranes. Therefore, the estimated growth of Nafion™ IXM dispersions has been calculated to be 51%.

Table 7-10: Total tonnes of Nafion™ IXM dispersions imported into the EU27/EEA		
Year	Lower bound	Upper bound
2021	0.1	0.2
2022	0.2	0.2
2023	0.2	0.3
2024	0.3	0.5
2025	0.5	0.8
2026	0.8	1.2
2027	1.2	1.8
2028	1.8	2.7
2029	2.7	4.1
2030	4.1	6.1
2031	6.2	9.2
2032	9.3	14.0
2033	14.1	21.1
2034	21.2	31.8
2035	32.0	48.1
Assessment period total	93	140
Grand total	95	142
Source: RPA study team analysis		

The quantity of Nafion™ IXM dispersions set to be imported into the EU will increase at similar levels to that of Nafion™ IXM membranes because they share similar properties and are just as vital to water electrolysis and fuel cell technology. Meaning that despite small quantities of material being imported even by 2035 the essentiality of Nafion™ IXM dispersions for their respective markets means a substantial downstream supply chain is still at risk if these small quantities were to be restricted. The combined use of Nafion™ IXM membranes and dispersions allow these fluoropolymer products to reach their maximum efficacy in terms of run time and overpotential for effective hydrogen and energy production. To that end Nafion™ IXM dispersions are also primarily set to be supplied to the water electrolysis market but there is the possibility for the estimated tonnages for fuel cell use to be higher if additional market demand and capacity for fluoropolymer containing cells for heavy goods vehicles is realised throughout Europe. Table provides this tonnage split between the two applications for Nafion™ IXM dispersions.

Table 7-11: Total tonnes of Nafion™ IXM dispersions imported by hydrogen economy use				
	Water electrolysis equipment		Fuel cells	
Year	Lower bound	Upper bound	Lower bound	Upper bound
2021	0.1	0.1	0.0	0.0
2022	0.1	0.2	0.0	0.0
2023	0.2	0.3	0.0	0.0
2024	0.3	0.5	0.0	0.0
2025	0.5	0.8	0.0	0.0
2026	0.8	1.2	0.0	0.0
2027	1.2	1.8	0.0	0.0
2028	1.8	2.6	0.0	0.0
2029	2.7	4.0	0.0	0.1
2030	4.0	6.0	0.0	0.1
2031	6.1	9.1	0.1	0.1
2032	9.2	13.8	0.1	0.2
2033	13.9	20.8	0.1	0.3
2034	21.0	31.4	0.2	0.4

Table 7-11: Total tonnes of Nafion™ IXM dispersions imported by hydrogen economy use				
	Water electrolysis equipment		Fuel cells	
Year	Lower bound	Upper bound	Lower bound	Upper bound
2035	31.7	47.4	0.3	0.6
Assessment period total	92	138	1	2
Grand total	94	140	1	2
Source: RPA study team analysis				

The value of Nafion™ IXM dispersions is substantially higher than that of Nafion™ IXM membranes meaning that the very low quantities of dispersions being imported can still form a substantial supply market with significant profits. Table and Table display the value of the import market which the Nafion™ IXM dispersions sold by Chemours APM are supplying. These estimates have been arrived at by multiplying the lower and upper bound of the 2021 tonnages, both in total and use specific, by the Nafion™ IXM dispersions lower bound sale price of €2.7 million and the upper bound price point of €9.1 million. This 2021 baseline figure was then grown in a compounded manner by 30% year on year up until the end of the assessment period in 2035, and then discounted at a rate of 4% from 2022 onwards.

Table 7-12: Total revenue from the sale of Nafion™ IXM dispersion imports		
Year	Lower bound (€)	Upper bound (€)
2021	260,000	1,310,000
2022	325,000	1,640,000
2023	406,000	2,050,000
2024	507,000	2,560,000
2025	634,000	3,200,000
2026	792,000	4,010,000
2027	990,000	5,010,000
2028	1,240,000	6,260,000
2029	1,550,000	7,820,000
2030	1,930,000	9,780,000
2031	2,420,000	12,200,000
2032	3,020,000	15,300,000
2033	3,780,000	19,100,000
2034	4,720,000	23,900,000
2035	5,900,000	29,800,000
Assessment period total	26,342,000	133,180,000
Grand total	28,474,000	143,940,000
Source: RPA study team analysis		

Table 7-13: Total revenue from the sale of Nafion™ IXM dispersions by hydrogen economy use				
	Water electrolysis equipment		Fuel cells	
Year	Lower bound (€)	Upper bound (€)	Lower bound (€)	Upper bound (€)
2021	257,000	1,300,000	2,600	17,500
2022	321,000	1,620,000	3,250	21,900
2023	402,000	2,020,000	4,060	27,300
2024	502,000	2,530,000	5,070	34,200
2025	627,000	3,160,000	6,340	42,700
2026	784,000	3,950,000	7,920	53,400
2027	980,000	4,940,000	9,900	66,800
2028	1,230,000	6,180,000	12,400	83,400
2029	1,530,000	7,720,000	15,500	104,000

Table 7-13: Total revenue from the sale of Nafion™ IXM dispersions by hydrogen economy use				
	Water electrolysis equipment		Fuel cells	
Year	Lower bound (€)	Upper bound (€)	Lower bound (€)	Upper bound (€)
2030	1,910,000	9,650,000	19,300	130,000
2031	2,390,000	12,100,000	24,200	163,000
2032	2,990,000	15,100,000	30,200	204,000
2033	3,740,000	18,800,000	37,800	255,000
2034	4,680,000	23,600,000	47,200	318,000
2035	5,840,000	29,400,000	59,000	398,000
Assessment period total	26,074,000	131,440,000	263,420	1,775,600
Grand total	28,183,000	142,070,000	284,740	1,919,200
Source: RPA study team analysis				

The market value of Nafion™ IXM dispersions over the course of the assessment period in total is set to be worth between €26.3 and €134 million. While this may be substantially smaller than that of the market for Nafion™ IXM membranes it is still a high value market given the quantity of material which is set to be imported. A small level of imports can generate a high value market within Europe and even larger downstream supply chain market thereby meaning these imports permit critical infrastructure within European supply chains to exist making the imports worthwhile. The same profit margin as Nafion™ IXM membranes has been applied to the revenues of Nafion™ IXM dispersions in order to arrive at the profits for dispersions and these profits are presented in Table and Table .

Table 7-14: Total profits from the sale of Nafion™ IXM dispersion imports		
Year	Lower bound (€)	Upper bound (€)
2021	191,000	967,000
2022	245,000	1,240,000
2023	313,000	1,580,000
2024	400,000	2,020,000
2025	512,000	2,590,000
2026	654,000	3,300,000
2027	817,000	4,130,000
2028	1,020,000	5,160,000
2029	1,280,000	6,450,000
2030	1,600,000	8,070,000
2031	1,990,000	10,100,000
2032	2,490,000	12,600,000
2033	3,120,000	15,800,000
2034	3,900,000	19,700,000
2035	4,870,000	24,600,000
Assessment period total	21,741,000	109,910,000
Grand total	23,402,000	118,307,000
Source: RPA study team analysis		

Table 7-15: Total profits from the sale of Nafion™ IXM dispersions by hydrogen economy use				
	Water electrolysis equipment		Fuel cells	
Year	Lower bound (€)	Upper bound (€)	Lower bound (€)	Upper bound (€)
2021	189,000	954,000	1,910	12,900
2022	242,000	1,220,000	2,450	16,500
2023	310,000	1,560,000	3,130	21,100
2024	396,000	2,000,000	4,000	27,000

Table 7-15: Total profits from the sale of Nafion™ IXM dispersions by hydrogen economy use				
	Water electrolysis equipment		Fuel cells	
Year	Lower bound (€)	Upper bound (€)	Lower bound (€)	Upper bound (€)
2025	507,000	2,550,000	5,120	34,500
2026	647,000	3,260,000	6,540	44,100
2027	809,000	4,080,000	8,170	55,100
2028	1,010,000	5,090,000	10,200	68,800
2029	1,260,000	6,370,000	12,800	86,100
2030	1,580,000	7,960,000	16,000	108,000
2031	1,970,000	9,950,000	19,900	134,000
2032	2,470,000	12,400,000	24,900	168,000
2033	3,090,000	15,500,000	31,200	210,000
2034	3,860,000	19,400,000	39,000	263,000
2035	4,820,000	24,300,000	48,700	328,000
Assessment period total	21,516,000	108,310,000	217,410	1,465,100
Grand total	23,160,000	116,594,000	234,020	1,577,100
Source: RPA study team analysis				

The high selling price and high profit margin allow the small quantity of Nafion™ IXM dispersion imports to generate profits for the European economy of a value between €21.7 and €110 million. Therefore, meaning that when combined with Nafion™ IXM membrane profits, the Nafion™ product line sold by Chemours APM returns a total beneficial value between €411 and €797 million over the course of the assessment period from 2026-2035.

7.3 Emissions

The inherent nature of fluoropolymers means they are not likely to release emissions due to their stability and inertness. Emissions may occur during processing and melting, however, emissions during use and end-of-life are not likely to occur. The large molecular weight of the fluoropolymers means it is unlikely to cross biological membranes, as well it is insoluble in water therefore there is no potential of toxicity to aquatic organisms. This section will look at emissions during the lifecycle of the product and what can be done to reduce emissions.

7.3.1 Emissions at the Dordrecht site in the Netherlands

There are no emissions related to the manufacture of Nafion™ IXM at the Dordrecht site. See Section 30 for information emissions abatement at Chemours' Dordrecht site and European facilities.

The investments Chemours has made is recognised by Dutch authorities who concluded "*no health risk is expected for people living in the vicinity of the Chemours Dordrecht plant due to exposure*"[88]. The additional measures being implemented to achieve their CRC 2030 goals will continue to lower emissions and exposure even further. To control emissions from fluoropolymer production, Chemours has invested in thermal converters. Thermal converters will completely convert the by-products of and the monomer and polymer plants to CO_2, H_2O, Hydrogen Fluoride (HF) and Hydrogen Chloride (HCl). Once HF and HCl are removed in the absorption column, flue gasses can be emitted.

[88] National Institute for Public Health and the Environment, Ministry of Health, Welfare and Sport, Evaluation of substances used in the GenX technology by Chemours, Dordrecht, 2016.

7.3.2 Lifecycle emissions

Nafion™ is not expected to degrade to an extent where particles of the polymer are emitted from the fuel cell or electrolyser during normal use. During the manufacture of MEAs, there may be Nafion™ offcuts from the cutting and manipulation of the membranes. These are considered as waste fluoropolymer material, which is collected and disposed of in the same way that membranes are disposed of at the end of life, as discussed in the following section. The volume of offcuts is anticipated to be very small and not of concern as businesses aim to reduce wastage of fluoropolymer materials due to their high cost point.

7.3.3 Waste management and end of life

At the end of use, fluoropolymers could be disposed of in the following manners: landfill, incineration, or reuse/recycling. Fluoropolymers are extremely stable and will not degrade in the environment or release hazardous substances. Due to the properties presented in Section 5, it can be inferred that fluoropolymers sent to landfill will not break down or transform and will remain in a landfill unless otherwise removed, owing to their persistency. Additionally, landfills in Europe are lined with HDPE and sealed off from the environment. Another common disposal method for fluoropolymers and PFAS in general is incineration. At high enough temperatures set out in the Industrial Emissions Directive 2010/75/EU of at least 850-1100°C for at least two seconds, the C-F bond will be broken destroying the fluoropolymers, and residual PFAS and hazardous substances formed during thermal decomposition. In Europe, typically 80% of fluoropolymers are sent to incineration. As mentioned in Section 5, the main thermal decomposition products of fluoropolymer incineration are HF and COF_2. The instability of COF_2 forms CO_2 and HF in the stack scrubbers. Emissions to the environment can be reduced up to a factor >99% with flue gas cleaning methods.

Recycling

In an ideal scenario, once an electrolyser or fuel cell reaches its end of life, the membrane will be recovered and re-used in a new device, forming a circular economy for the fluoropolymer material.

There are known methods for recycling of catalyst coated membranes (CCMs) which involve the dissolution of the membrane in an appropriate solvent system, generating a slurry of dissolved Nafion™ and suspended catalyst particles. The slurry is then filtered to separate the two components, after which the Nafion™ membrane can be reprocessed into a new membrane material.[89]

While this recycling process is theoretically possible, there are concerns that the Nafion™ material which is recovered will be of a grade too low for use in new fuel cell or electrolyser devices. As a result of these concerns, recovery of Nafion™ from failed MEAs is not generally attempted.[90]

Incineration

An currently suitable method of disposal for expired Nafion™ membranes is incineration. This is carried out to effectively remove the catalyst layer from the membrane so that the catalyst can be recovered and recycled. Since the incineration process is carried out with the intention of recovering the precious metals from the catalyst, incineration of CCMs must be done in a specialised facility.

89 https://en.kunststoffe.de/a/article/article-264236 accessed September 2022
90 pro-K Fachgruppe Fluoropolymergroup (pro-kunststoff.de) accessed September 2022

The incineration products of Nafion™ and fluoropolymers in general vary depending on the specific temperature, the presence of water or oxygen, and the use of a catalyst for decomposition. There are conflicting reports on the nature of fluoropolymer decomposition products, with some studies indicating that incineration products of fluoropolymers are generally comprised of hydrogen fluoride and short chain perfluoroalkanes such as CF_4, C_2F_6 and others, while others suggest that complete mineralisation of C-F bonds occurs.[91]

Some of the proposed decomposition materials are extremely toxic (in the case of hydrogen fluoride) or have high GWPs (in the case of small perfluoroalkanes) and therefore care must be taken during incineration processes to avoid generation of these concerning substances. In cases where generation of these materials cannot be avoided, all care must be taken to prevent their release into the environment.

If the incineration temperature is sufficiently high (i.e., above 1000°C), then all C-F bonds are broken and the HF which is released can be captured by alkaline scrubbers, where all fluorine is converted to calcium fluoride[92].

Landfill

Nafion™ waste is often disposed of by landfill, particularly if no further treatment is required to extract the catalyst material from the membrane at the end of life. Since Nafion™ is extremely stable, and does not decompose when exposed to UV light, oxygen, freshwater, saltwater, or bacteria it is not expected to degrade within the landfill and therefore does not pose a risk of contaminating the environment[93].

7.4 Value of downstream markets

7.4.1 Fuel cells

The global fuel cell market is rapidly developing and is driven by investments to establish hydrogen structures and the push to establish and accelerate clean energy alternatives[94]. Coupled with European strategies to reduce carbon emissions, clean power generation through hydrogen fuel cells will continue to drive the market. In 2022, the global fuel cell market was worth $2.9 billion and is expected to increase to $9.1 billion by 2027, with a CAGR of 26% through the forecasted period[95]. Proton exchange membrane fuel cells dominated the market with is main application being for

91 https://nilu.brage.unit.no/nilu-xmlui/bitstream/handle/11250/2561710/NILU%2BOR%2B12-2009.pdf accessed September 2022
92 Per- and polyfluorinated substances in waste incinerator flue gases (rivm.nl) accessed September 2022
93 Ruwona and Henry 2021. PTFE: Persistence without hazard at environmentally relevant temperatures and durable by design. Fluoros 2021, Providence, R.I.
94 https://www.gminsights.com/industry-analysis/fuel-cell-market accessed September 2022
95 https://www.marketsandmarkets.com/Market-Reports/fuel-cell-market-348.html accessed September 2022

transportation, followed by solid oxide fuel cells[96]. The PEMFC market size was $1.56 billion in 2020 is projected to grow from $2.10 billion in 2021 to $22.74 billion in 2028 at a CAGR of 40.6%[97].

More specifically, Chemours' fuel cell market size is estimated to be $772 million by 2026 with a CAGR of 70% through the forecasted period of 2021 – 2026[98]. The global automotive fuel cell market is expected to grow from $1.73 billion in 2021 to $34.63 billion in 2028[99]. Asia held the biggest market share, with Europe not far behind. Fuel cell membranes for vehicles is estimated to be $51M in 2021 and is predicted to grow to $718 million by 2026 with a CAGR growth of 70%. Catalyst dispersion is predicted to be $54 million in 2026 with a CAGR of 68% between 2021 – 2026. The use of heavy-duty fuel cell membranes is forecasted to grow from $12 million in 2021 to $856 million in 2026 with a CAGR between 2021-2026 to be 89%. Chemours has predicted a heavy-duty fuel cell market size of $394 million with a growth rate of 109% between 2020-2025.

7.4.2 Water-electrolysis

The PEMWE market was estimated to be $359 million in 2021 and is predicted to grow to $7,178.6 million by 2031, at a CAGR of 35.4%[100]. Europe is known to be the majority shareholder with over 55% share of the market[101]. While alkaline electrolysers currently hold the highest share of the global market (33%), PEMWEs are expected to hold most of the market by 2030[102] Chemours market share for 2025 is conservatively estimated to be $37 million with a predicted CAGR of 106% between 2020-2025, however with the unpredictable energy landscape, this value is likely to be a vast underestimate.

7.4.3 Nafion™ IXM membranes in the hydrogen economy

The Nafion™ IXM membrane downstream supply chain is rather complex due to its multiple prongs and end users. On one part there is the clean hydrogen generation arm which consists of MEA manufacturers and water electrolysis equipment manufacturers which then supply equipment to downstream users who would focus on hydrogen generation and supply and renewable energy conversion. The other element of the supply chain is the fuel cell supply chain which consists of MEA manufacturers, fuel cell stack manufacturers and then various OEM manufacturers where the focus for this SEA was on operation dedicated to the heavy-duty fuel cell supply chain. **Error! Reference source not found.** provides a diagrammatical explanation of the hydrogen economy supply chain.

96 https://www.fortunebusinessinsights.com/industry-reports/fuel-cell-market-100733 accessed September 2022

97 https://www.fortunebusinessinsights.com/industry-reports/proton-exchange-membrane-fuel-cell-pemfc-market-101708 accessed September 2022

98 https://investors.chemours.com/events-and-presentations/event-details/2021/Advanced-Performance-Materials-Investor-Webinar/ accessed September 2022

99 https://www.globenewswire.com/en/news-release/2022/05/09/2438228/0/en/Automotive-Fuel-Cell-Market-Size-to-Hit-USD-34-63-Billion-by-2028-Fuel-Cell-Industry-Analysis-by-Share-Trends-And-Growth-Forecast.html accessed September 2022

100 https://bisresearch.com/industry-report/water-electrolysis-market.html1pfhnKn8XQtNrdhF4kpvEcxeKyXROrxVkNJkQrS4JVycaAtUKEALw_wcB accessed September 2022

101 https://www.gminsights.com/industry-analysis/electrolyzer-market accessed September 2022

102 Electrolyzer Market Size & Share | Forecast Report 2022-2030 (gminsights.com) accessed September 2022

7.4.3.1 MEA manufacturers

Some membrane electrode assembly (MEA) manufacturers responded to RPA's consultation questionnaire but there were not enough respondents to provide an accurate deception of the market based on consultation data alone. Therefore, the RPA study team sought to supplement their consultation findings with publicly available data. It was discovered that the global MEA market is estimated to generate revenues and be valued at just over 682 million Dollars in 2022 and is set to grow at a CAGR of 20.84%[103]. Using a dollar to Euro conversion ration from the 1st of September 2022 of 1:1 this equates to a global value of €682 million. The study team also established that the European share of this market currently stands at around 16.9% with this adjusting to just over 13.5% by the end of 2035 as other global markets in North America and China are set to develop more rapidly than the European market[104]. This enabled the study team to estimate the revenues generated by European MEA producers and via application of the industry average profit margin of 6.3% for NACE classification C27.20 obtained from Eurostat European MEA profits could also be obtained. This information is presented in Table 7-16 and all values have been discounted from 2023 onwards at a discount rate of 4%.

Table 7-16: European membrane electrode assembly revenues and profits

Year	Global MEA revenues ($)	European share	European MEA revenues (€)	European MEA profits (€)
2022	682,000,000	16.93%	116,000,000	7,280,000
2023	793,000,000	16.37%	130,000,000	8,180,000
2024	921,000,000	15.81%	146,000,000	9,180,000
2025	1,070,000,000	15.25%	163,000,000	10,300,000
2026	1,240,000,000	14.69%	183,000,000	11,500,000
2027	1,450,000,000	14.13%	204,000,000	12,900,000
2028	1,680,000,000	13.57%	228,000,000	14,400,000
2029	1,950,000,000	13.57%	265,000,000	16,700,000
2030	2,270,000,000	13.57%	308,000,000	19,400,000
2031	2,630,000,000	13.57%	357,000,000	22,500,000
2032	3,060,000,000	13.57%	415,000,000	26,200,000
2033	3,560,000,000	13.57%	483,000,000	30,400,000
2034	4,130,000,000	13.57%	561,000,000	35,300,000
2035	4,800,000,000	13.57%	652,000,000	41,000,000
Assessment period total	26,770,000,000		3,656,000,000	230,300,000
Grand total	30,236,000,000		4,211,000,000	265,240,000

Source: RPA study team analysis

It is assumed that all MEA materials are manufactured from fluoropolymer materials particularly Nafion™ IXM. Therefore, it is estimated that **over the assessment period European MEA manufacturers will generate profits and economic returns in the order of just over €230 million.** This is likely to be an underestimation given NACE industry average profit margin which is applied and respondents to RPA's consultation indicated that higher profit margins of potentially double the stated figure could be experienced, the above estimate is therefore conservative. There is also a certain level

103 https://www.marketwatch.com/press-release/membrane-electrode-assemblies-mea-market-size-2022-global-business-growth-industry-revenue-demand-and-applications-market-research-report-to-2028-2022-09-13 accessed September 2022

104 https://www.marketresearch.com/QYResearch-Group-v3531/Global-Membrane-Electrode-Assemblies-MEA-31700874/ accessed September 2022

of variability in the above estimation given that if Europe were to push greater into green hydrogen generation and hydrogen fuel cells they may retain more of the global market and thus increasing the revenues and profits of European manufacturers. Given the limited responses to consultation and the amalgamated nature of the NACE C27.20 classification it has not been possible to accurately identify the number of enterprises operating within Europe within the MEA market segment.

7.4.3.2 Water electrolysis equipment manufacturers

Due to the small number of respondents who identified as a water electrolysis equipment manufacturer no survey responses could be processed and presented in this report without disclosing identifiable confidential information about market operators. The RPA study team therefore looked to publicly available data sets to value the water electrolysis equipment downstream user market. Unfortunately, publicly available data which referenced electrolysis equipment was too amalgamated for the study team to decern the information which was relevant only to water electrolysis equipment. Consequently, the study team have been unable to estimate the value generated by the water electrolysis equipment market over the assessment period and the number of enterprises estimated to be involved within this market.

7.4.3.3 Hydrogen fuel cell manufacturers

Some hydrogen fuel cell manufacturers responded to RPA's consultation questionnaire but there were not enough respondents to provide an accurate deception of the market based on consultation data alone. Therefore, the RPA study team sought to supplement their consultation findings with publicly available data. By use of the PRDCOM code 27.90.42.00 in Eurostat the RPA study team were able to establish that over €128 million worth of fuel cells were manufactured in 2021. The study team also through desk research established that the fuel cell market is estimated to grow at a CAGR of 19.4%[105] and as such the study team grew this 2021 revenue figure by this CAGR for the assessment period. This PRODCOM code however includes fuel cells which are manufactured with materials other than Nafion™ IXM and so the study team sought to identify what proportion of fuel cells are manufactured with PFAS materials. Via additional desk research it was identified that roughly 66% of all fuel cells are classed as proton exchange membrane fuel cells (PEMFC)[106] and most of these types of cells use Nafion™ IXM. By applying this 66% ratio a growth rate of 19.4% and a profit margin of 9.5% which was extracted from Eurostat as the average profit margin for enterprises under NACE classification C27.90 the study team have been able to estimate the revenue and profits of European based hydrogen fuel cell manufacturers using Nafion™ IXM and these discounted estimates are presented in Table 7-17.

Table 7-17: European fuel cell revenue and profits

Year	European FC revenues (€)	European PEMFC revenues (€)	European PEMFC profits (€)
2021	128,000,000	84,500,000	8,030,000
2022	153,000,000	101,000,000	9,580,000
2023	175,000,000	116,000,000	11,000,000
2024	201,000,000	133,000,000	12,600,000
2025	231,000,000	153,000,000	14,500,000
2026	266,000,000	175,000,000	16,600,000

105 https://www.alliedmarketresearch.com/fuel-cell-market accessed September 2022

106 https://www.fortunebusinessinsights.com/industry-reports/fuel-cell-market-100733 accessed September 2022

Table 7-17: European fuel cell revenue and profits			
Year	European FC revenues (€)	European PEMFC revenues (€)	European PEMFC profits (€)
2027	305,000,000	201,000,000	19,100,000
2028	350,000,000	231,000,000	21,900,000
2029	402,000,000	265,000,000	25,200,000
2030	461,000,000	304,000,000	28,900,000
2031	530,000,000	350,000,000	33,200,000
2032	608,000,000	401,000,000	38,100,000
2033	698,000,000	461,000,000	43,800,000
2034	801,000,000	529,000,000	50,200,000
2035	920,000,000	607,000,000	57,700,000
Assessment period total	5,341,000,000	3,524,000,000	334,700,000
Grand total	6,229,000,000	4,111,500,000	390,410,000
Source: RPA study team analysis			

Over the course of the assessment period European fuel cell manufacturers using Nafion™ IXM will generate revenues estimated at over €3.5 billion which will produce profits of over €334 million. Again, these estimates are likely to be underestimates given the low industrial average profit margin which has been applied to the public data extracted from Eurostat.

7.5 Health and environmental impacts

7.5.1 Health impacts

Based on the information available and because there is no production within the EU of Nafion™, health hazards are not of concern. Therefore, the health impacts under a continued use scenario have not been calculated. Companies and their employees should be familiar with "*The Guide to the Safe Handling of Fluoropolymer Resins*," published by PlasticsEurope[107]. These guidelines demonstrate what is expected when handling fluoropolymer resins in the workplace. Additionally, monomer plants are typically outdoors while polymer production plants are indoors.

7.5.2 Environmental impacts

Based on the information available, the environmental concerns for Nafion™ relate to its persistency. Fluoropolymers can be landfilled at the end of life and because they are stable and will not break down in the environment, they are considered environmentally neutral[108]. During consultation with downstream users, it was implied that the majority of Nafion™ membranes will be incinerated at the end of life to recover the precious metals bound to the membrane as discussed in section 7.3.3.

[107] *Guide for the Safe Handling of Fluoropolymer Resins*. (2021). https://fluoropolymers.plasticseurope.org/application/files/6216/3178/0517/Fluoropolymers_Safe_Hand_EN__June_2021.pdf accessed September 2022

[108] https://fluoropolymers.plasticseurope.org/application/files/6216/3178/0517/Fluoropolymers_Safe_Hand_EN__June_2021.pdf accessed September 2022

7.6 Employment

7.6.1 Chemours APM

Chemours APM has an employment footprint that includes several European nations. One of these is Switzerland but due to Switzerland being outside the EU27/EEA zone employment figures for this country have been excluded from consideration. A total of six Member Sates benefit from employment as a result of Chemours APMs operations and these roles vary from direct and 'hands-on' roles such as those manufacturing, packaging and transporting products to more functionary roles such as sales teams, compliance and HR for example. The Member States benefiting from this employment are the Netherlands, Belgium, France, Spain, Germany, and Denmark and across these nations APM employ a total of 629 full time equivalent employees each of whom are paid an average salary of €70,000. This high salary is due to the technical and specialist nature of APM's operations which makes the skillset of this workforce very high and their pay considerably above the standard European benchmark figure of €30,000. Employment is beneficial for any Member state or economy to experience, the RPA study team has conducted research to quantify, in a justifiable way, the extent of this benefit for each nation.

The RPA study team first quantified how much of each employee's salary will be used to make tax and social security contributions. The study team then determined how much of the employee's income will be removed from general money supply via savings (the household saving ratio) and subsequently how much disposable income each employee will have to drive economic activity and growth via consumption. These factors are reported in Table . All tax calculations have been estimated on a "most expensive" scenario whereby the highest possible tax bill for an individual has been estimated by assuming all individuals are unmarried and have no dependents. The tax income per person is therefore likely to be an overestimation of the true tax bills most of these individuals would face and subsequently national tax receipts would be lower. The household saving ratio is the percentage of a person's gross disposable income which is saved within a set period of a year, this value is typically reported by country quarterly but there are large variations in the frequency at which nations report this statistic. For reference the values reported below for the Netherlands relate to the saving ratio as of September 2021, the values for Belgium, Spain and Denmark refer to the rate as of December 2021 and for Germany and France the reported rate is from March 2022.

Table 7-18: Economic contribution of employment from Chemours APM European operations

Member State	Number of Employees[1]	Average Salary (€)[1]	Tax income per person (€)[2]	Net pay (€)	Household saving ratio[3]	Disposable income per person (€)
Netherlands	464.9	70,000	22,178	47,822	16.31%	40,022
Belgium	76.2	70,000	30,719	39,281	12.50%	34,371
France	66.3	70,000	26,541	43,459	17.36%	35,915
Spain	15	70,000	22,418	47,582	13.81%	41,011
Germany	5.7	70,000	27,767	42,233	11.50%	37,376
Denmark	1	70,000	30,674	39,326	8.17%	36,113

[1] *Source: Chemours APM consultation*
[2] *Source: https://salaryaftertax.com/ - for France, Spain, Belgium and Germany; https://www.icalculator.info/netherlands/salary-calculator/annual/2022.html - for the Netherlands; https://www.icalculator.info/denmark.html - for Denmark*
[3] *Source: https://tradingeconomics.com/country-list/personal-savings accessed 6th June 2022*

As can be seen from the above table, Member States could be receiving approximately €22,000 to €31,000 per employee thanks to Chemours APM operations. Consequently, European governments could receive tax receipts of up to a maximum of just over €14.9 million per year. This funding would be used to finance fiscal policy in member states which would allow for economic growth through government expenditure therefore meaning that this €1.5 million per year would be greater as it would be subject to a government expenditure multiplier, but this cannot currently be estimated for each member state due to data constraints.

Likewise, after deducting the average household saving ratio, employees of APM have between €34,000 and €41,000 each to spend in disposable income per year. Theoretically not all this income would be truly disposable as each individual employee would have a basic level of consumption, they would have to spend to live, and some would be required to service household debt. However, whether this income was being spent on luxury items, servicing debt, or satisfying basic level consumption needs, consumption and economic activity would be taking place allowing economic growth to take place. In fact, per year Chemours APM employees through their disposable income would be able to contribute over €24.4 million in economic activity, which would bring the total yearly economic contribution of these employees to just over €39.4 million. This would also be subject to a separate consumption-based multiplier but once again due to data constraints and individual member state complexities it is not currently possible to accurately predict these multipliers but the returns to national and the wider European economy from Chemours APM employment is self-evident and substantial once multiplied. The total contributions made to each member state's economy and the European economy have been summarised in Table .

Table 7-19: Economic contributions of Chemours APM employees by Member State

Member State	Total tax receipts (€)	Total disposable income (€)	Total (€)
Netherlands	10,300,000	18,600,000	28,900,000
Belgium	2,340,000	2,620,000	4,960,000
France	1,760,000	2,380,000	4,140,000
Spain	336,000	615,000	951,000
Germany	158,000	213,000	371,000
Denmark	30,700	36,100	66,800
Total	14,900,000	24,500,000	39,400,000

Source: RPA study team analysis

Chemours APM employees are therefore able to make a significant annual contribution to the wider and national economies given their large average salary and the number of staff employed. The final form of analysis to assess the contribution of these employees by the RPA study team was to extrapolate these contributions across the duration of the assessment period and discount at the appropriate 4% rate. The results of this are found in Table .

Table 7-20: Discounted annual estimate of economic contribution from Chemours APM employees

Year	Economic contribution (€)
2022	39,400,000
2023	37,900,000
2024	36,400,000
2025	35,000,000
2026	33,700,000
2027	32,400,000
2028	31,100,000

Table 7-20: Discounted annual estimate of economic contribution from Chemours APM employees	
Year	**Economic contribution (€)**
2029	29,900,000
2030	28,800,000
2031	27,700,000
2032	26,600,000
2033	25,600,000
2034	24,600,000
2035	23,700,000
Assessment period total	284,100,000
Grand Total	432,800,000
Source: RPA study team analysis	

Therefore, as can be seen above over the course of the assessment period from 2026 to 2035 the 629 full time equivalent positions related to Chemours APM operations will generate a total discounted contribution to the wider European economy of over €284 million. Once again however it should be noted this value is likely to be considerably higher as these figures will be subject to government spending, money, and consumption multipliers but these multipliers cannot currently be accurately estimated. While the whole of the European economy benefits from this employment and these greater levels of spending the impacts are not evenly distributed with countries such as the Netherlands, Belgium and France being in receipt of the majority of employment benefits from APM under the continued use scenario this is not an issue as while some member states are receiving a greater share of returns the whole economy is receiving economic contributions from this employment but it is an indicator that under a non-use scenario the impacts of unemployment will not be evenly and some member states will be more disproportionately affected than others and this is discussed more in Section 8.6.

7.6.2 Hydrogen economy

During the consultation phase the RPA study team received only limited responses from companies within each of the three downstream user markets being explored within this SEA. Due to the limited number of responses the data that was provided is unable to be presented in this SEA, for confidentiality reasons. The Eurostat data for the MEA producers, water electrolysis equipment manufacturers, hydrogen fuel cell manufactures, and heavy-duty hydrogen fuel cell powered vehicles was also not able to be presented. This is due to the data for these downstream uses coming under large NACE codes which contained amalgamated data and with these downstream markets being quite niche there is no further breakdown provided by Eurostat. Considering the lack of data gathered from the consultation phase it was also not possible to estimate the proportion of the NACE codes in question can be attributed to the specific downstream market segments.

In 2020 hydrogen fuelled vehicles made up less than 0.01% of the global stock of all vehicles and only 0.3% of electric vehicles. Heavy-duty hydrogen powered vehicles is still a relatively new market with many manufacturers currently still at testing and initial roll out phases. Globally heavy-duty fuel cell vehicles (FCVs) account for 25% of all FCV stock (with the other 75% being light duty consumer vehicles) at the end of 2020. In 2021 there was just over 3,000 FCVs within Europe, if it is assumed that Europe has the same percentage split as is seen globally then this would result in approximately 750 heavy-duty FCEVs with Europe[109].

In 2020 there were over 435 thousand trucks manufactured within the European Union, with 54 factories producing trucks across the continent. Considering the European Union's plan to end the sale of vehicles with combustion engines within Europe by 2035, and that hydrogen fuel seems to be preferred green fuel alternative for HDVs in Europe, this could result in production of heavy-duty FCEV being scaled up to supply this level of demand[110]. Therefore, there are large opportunities for growth in employment within the heavy-duty hydrogen fuel cell vehicle market, but the current levels of employment and its benefits cannot be accurately estimated.

7.7 Innovations and investments

7.7.1 Chemours APM

Chemours APM is a global company meaning it has a global footprint for its research and development (R&D) and capital investment activities. Currently some R&D activities take place within Europe which are conducted by APM. Given that most of the business operations of the Chemours APM division are associated with fluoropolymers, most of their R&D spending is also connected to the development of fluoropolymers on two fronts. The first area of focus for research and development is the continued development of new manufacturing processes, products, and applications of existing fluoropolymer technologies to open new markets allow downstream supply chains to grow and to develop greater efficiencies in production. The annual value of these investments from APM amount to €27.6 million. The second area of focus for Chemours APM's research and development spending is in the field of alternatives research. APM take a proactive role in the research of alternatives to PFAS materials which deliver the same or better results than their current portfolio of goods or manufacturing processes. To this end during consultation and in their questionnaire response APM indicated investing annually €13.1 million into R&D activities dedicated to exploring and assessing possible alternatives to PFAS materials, such as replacing polymerisation aids in manufacturing processes. Therefore, meaning a combined total of around €40.7 million are invested annually by Chemours APM into research and development activities. These investments have returned some positive results so far in terms of discovering viable alternatives to PFAS materials. For example, a recent announcement from Chemours discussed the commercialisation of an alternative to fluorinated surfactants in one product line. Although this is not directly related to Nafion™ IXM, it is still a positive outcome to R&D investments made by Chemours. Under a non-use scenario these investments and research efforts would not continue due to there being no business portfolio to fund R&D activities. The discounted annual value of this research and development spending is presented in Table 7-21.

Table 7-21: Discounted annual R&D spending			
Year	Total PFAS R&D (€)	Operational R&D (€)	Alternatives R&D (€)
2021	40,700,000	27,500,000	13,100,000
2022	39,100,000	26,500,000	12,600,000
2023	37,600,000	25,500,000	12,100,000
2024	36,100,000	24,500,000	11,700,000
2025	34,800,000	23,500,000	11,200,000
2026	33,400,000	22,600,000	10,800,000

109 https://www.iea.org/reports/hydrogen accessed September 2022

110 https://hydrogeneurope.eu/wp-content/uploads/2022/04/Jorgo-Chatzimarkakis-Hydrogen-The-key-fuel-for-trucks-27-April.pdf accessed September 2022

Table 7-21: Discounted annual R&D spending			
Year	Total PFAS R&D (€)	Operational R&D (€)	Alternatives R&D (€)
2027	32,100,000	21,800,000	10,400,000
2028	30,900,000	20,900,000	9,970,000
2029	29,700,000	20,100,000	9,580,000
2030	28,600,000	19,300,000	9,220,000
2031	27,500,000	18,600,000	8,860,000
2032	26,400,000	17,900,000	8,520,000
2033	25,400,000	17,200,000	8,190,000
2034	24,400,000	16,500,000	7,880,000
2035	23,500,000	15,900,000	7,570,000
Assessment period total	281,900,000	190,800,000	90,990,000
Grand total	470,200,000	318,300,000	151,690,000
Source: RPA study team analysis			

After discounting at the 4% ECHA rate the total amount of **R&D investment Chemours APM will make in Europe over the course of the 2026-2035 assessment period stands at over €281 million with over €90.9 million of this being dedicated to the exploration of alternatives.**

7.7.2 Downstream user investments

7.7.2.1 MEA manufacturers

As the segment of the supply chain who are directly responsible for the conversion of Nafion™ into the main electrochemical components of water electrolysis or fuel cell modules, it is expected that MEA manufacturers have the most scope for developing alternative membrane materials. This was confirmed to be the case where all MEA manufacturer respondents of the questionnaire indicated that they are either currently investing in R&D towards finding alternative materials or had previously invested in R&D which had now concluded. Little information regarding the size of these investments was provided to the RPA study team, however from the data provided, it appears that an average expenditure in the hundreds of thousands of Euros per year is typical for research into alternative membrane materials. As the demand for fuel cells and water electrolysis equipment grows to meet the net-zero carbon targets set out in recent years by the EU, significant investment into the supply of MEAs containing Nafion™ is required to meet this demand.

7.7.2.2 Fuel cell equipment manufacturers

Fuel cell stack manufacturers are supplied with MEAs which are already fitted with the membrane material. To manufacture a stack, multiple MEAs are connected to fit the power requirements of the fuel cell. Module manufacturers then fit the balance of plant such as water and heat management systems. As such, there is little work done that directly involves Nafion™ membranes and therefore it is expected that the responsibility for stack and module manufacturers to develop new membrane materials is less than that of the MEA manufacturers. Indeed, during consultation, those companies who were not involved in the conversion of Nafion™ into MEAs did not indicate any R&D investment into alternative membrane materials.

7.7.2.3 Water electrolysis equipment manufacturers

Like fuel cell manufacturers, water electrolyser manufacturers receive MEAs from the supply chain and form stacks and modules from these MEAs where little work is done on the development of the membrane itself. With the rapidly increasing demand for water electrolysis equipment within the EU, multiple companies are currently seeking to build new factories to meet this demand. Each of these factories require tens of millions of Euros in investment to provide the specialist equipment and highly skilled staff needed.

7.8 Summary

The activities of the Chemours APM division under review in this socio-economic analysis is the importation of Nafion™ IXM for sale into the various supply chains within the hydrogen economy in Europe. The supply chains in question have been the manufacture of water electrolysis equipment to produce green hydrogen and the manufacture of hydrogen fuel cells with particular focus on heavy-duty fuel cells. This report has sought, where possible, to monetise and value the operations of both Chemours and the actors in these relevant supply chains.

The RPA study team have estimated that under the continued use scenario over the course of the assessment period between the start of 2026 and the close of 2035 the European market for Nafion™ IXM will provide substantial wealth for the European economy. On the part of Chemours APM their combined operations within scope of this study will generate profits valued at between €411 and €797 million over the assessment period. Initiatives such as the EU Green Deal and REPowerEU are creating a drive-in demand for greener energy sources with green hydrogen generation being a key area for growth under this programme. Therefore, demand for water electrolysis equipment and hydrogen fuel cells are set to see very rapid and sustained growth over the coming decade which in turn is creating a greater demand for Nafion™ IXM.

Nafion™ IXM is not manufactured or processed by Chemours in Europe, therefore no emissions take place at Chemours' sites in Europe. In addition, no or very limited emissions during use are expected due to the closed systems used in the manufacture of articles. Nafion™ IXM has no known human health effects and no known environmental hazards and is not classified as PBT. It is however a persistent substance, and this level of persistency is evaluated in terms of emission levels. Due to no health and environmental hazards being present there are no associated health and environmental costs under the continued use scenario.

The hydrogen economy consists of two supply chains and across these, three markets have been identified: the MEA manufacture market, the water electrolysis equipment market, and the hydrogen fuel cell market. The MEA manufacture market is estimated over the course of the assessment period to experience rapid growth for the reasons mentioned above and will ultimately generate over €3.6 billion in revenue, resulting in an economic contribution of over €230 million. The revenues and profits generated by water electrolysis equipment manufacturers could not be estimated due to limited consultation response and the quality of publicly available data. Hydrogen fuel cell manufacturers are estimated over the assessment period to generate over €3.5 billion in profit returning an economic benefit of over €334 million. **Therefore, the total minimum economic contribution of Nafion™ IXM activities within scope of this SEA are estimated at between €976 million and €1.4 billion.**

In addition to this, these markets are generators of substantial employment and employment value for the European economy. Chemours APM by the start of the assessment period will employ around 629 staff across the EU which will provide economic returns to the economy over the assessment period of over €284 million. The total number and value of employment generated by the hydrogen economies supply chains has not been possible to calculate given the lack of response to consultation during this SEA and the quality of publicly available data. However, it is anticipated that this market while growing substantially will generate high value employment through high wages due to the skill level required to operate in this industry.

At present Chemours APM have a diverse range of projects in their research and development portfolio across several sites within Europe. **Over the assessment Chemours APM will spend nearly €91 million on PFAS alternative R&D**, while also spending an additional €190 million on operational R&D to develop and improve their manufacturing processes and logistics chains. This level of spending is only possible under the continued use scenario as without the sale of PFAS products such as Nafion™ IXM there would be no business operation to fund the projects they are conducting. Downstream users in the hydrogen economy are not spending R&D budgets on the development of new alternatives to PFAS and Nafion™ IXM but are testing the validity of alternative materials. They are however conducting operational R&D spending to improve their processes and efficiency.

Finally, as well as generating substantial value in terms of profits generated and well-paid employment the Nafion™ IXM market and its downstream users are essential to the development and achievement of critical EU objectives and strategies. A total of four European objectives and strategies were identified as being dependent on the Nafion™ IXM market in some capacity. Policies such as the European Green Deal, the EU hydrogen strategy, the European clean hydrogen alliance and REPowerEU are dependent on the hydrogen economy and therefore dependent on the supply of Nafion™ IXM. Access to materials such as Nafion™ IXM will allow the hydrogen economy to expand and produce green hydrogen and produce more hydrogen fuel cells which will permit a smoother transition to a decarbonised European economy, but this smooth transition is only possible under a continued use scenario.

8 Non-use scenario

8.1 Introduction

This section outlines the non-use scenario for the APM division of Chemours and its downstream users in relation to the import, export, sale, and use of fluoropolymers. There are many different forms a non-use or restriction scenario can take due to the various conditions that can be laid out in a restriction proposal. These conditions can range from a total restriction on the manufacture and sale of a chemical product to limitations on the concentrations used during the manufacturing process or present in finished articles. The non-use scenario that has been assumed by the RPA study team is one of a total restriction (ban) on the import, manufacture, sale, and use of fluoropolymers within the EU27/EEA. It is therefore assumed for the purposes of this assessment that from the start of 2025 APM will have 6 months to phase out and cease their import, and manufacture of all fluoropolymer products in Europe with a further 6 months to sell all remaining stocks. This situation will also apply to the downstream customers of APM who, will also have 6 months to scale down and cease the purchase and use of fluoropolymers with a further 6 months to sell their remaining stocks of articles containing fluoropolymers. Therefore, the first year of no PFAS related activities is assumed to be 2026 and this is the year for which first year losses are calculated and presented.

This non-use scenario was chosen due to it being the most extreme option possible under a REACH restriction. Therefore, utilisation of this scenario allows the RPA study team to present the worst-case scenario for both Chemours APM and the European economy. Other, less extreme, restriction situations may result in smaller damages being suffered by the European economy, but it should also be noted that many restriction conditions such as limits on permitted concentrations of fluoropolymers would also equate to de-facto ban on fluoropolymer usage within the EU27/EEA given the way in which the material is utilised. The results presented under this most extreme of restriction scenarios are therefore representative of the outcomes APM and the European economy would face under many different variations of restriction.

The non-use scenario will be the mirror image to the continued use scenario discussed in Section 0, thereby meaning this section will continue to focus on the import and sale of Nafion™ IXM for use within the manufacture of fluid handling/chemical distribution equipment used in the manufacture of semiconductors and the hydrogen economy covering water electrolysis equipment and hydrogen fuel cells. The information presented in this section will be specific to these two end uses of fluoropolymers supplied by APM but there will also be higher level generalisations and extrapolations to the wider context of these markets alongside discussion of impacts on other markets related to the in-scope markets.

The timeline for the assessment of the impacts suffered under the non-use scenario is a 10-year period from 2026 to 2035. This timeline has been used by the RPA study team due to the current lack of suitable and scalable alternatives to fluoropolymers in the applications being assessed and the time horizons that will be required to develop new materials. Alternatives to Nafion™ IXM in the hydrogen economy have been explored for quite some time, such as hydrocarbon-based electrolysers and fuel cells which have been explored and tested by some downstream users for more than 10 years before they have ultimately been deemed unfit for purpose within the sector. These same downstream users and manufacturers within the sector have agreed that a 10-year period is the minimum possible time horizon it would take for an alternative to be thoroughly explored in terms of functionality and market scalability. Therefore, as there are currently no suitable alternatives to Nafion™ IXM within this sector after a restriction is implemented it will be over 10 years before any possible alternative can enter the market to review and transform the hydrogen economy sector within Europe therefore it is logical for a 10-year assessment period of losses related to Nafion™ IXM to be employed.

8.2 Import and profit losses

8.2.1 Nafion™ IXM membrane import, and profit loses

The Nafion™ IXM market will be brought to a value of zero under the assumed non-use scenario with the importation and use of Nafion™ IXM being prohibited. Water electrolysis equipment and fuel cells would no longer be able to utilise the efficient and long last technology of Nafion™ IXM membranes. The hydrogen economy itself would not cease to exist as there are other methods of generating hydrogen as previously mentioned but these are far less environmentally friendly compared to water electrolysis and less cost effective as well. Therefore, the hydrogen economy in Europe under a non-use scenario would become inferior to that of the hydrogen economy in other parts of the world. In addition to the establishment of a subpar market the European economy would also suffer the loses as presented tables in below.

The loss of the Nafion™ IXM market for use within the hydrogen economy will generated losses for the European economy and lost profits for Chemours APM in the region of €389 to 687 million (see section 7.2.1 for calculations)**.** In addition to this between €132 million and €190 million in profits will be lost due to sales of Nafion™ IXM for other uses also being halted. Nafion™ IXM membranes however as previously discussed have an associated product with their functionality which is Nafion™ IXM dispersions, the losses that would be realised from this application also being impacted would be compounded with the loses of Nafion™ IXM membrane sales.

8.2.2 Nafion™ IXM dispersion import, and profit loses

Nafion™ IXM dispersion imports also being reduced to zero will incur an economic loss in the region of €21.7 to €110 million in lost profits (see section 7.2.2 for calculations). The combined profit losses of both Nafion™ IXM membranes and dispersions for use within the hydrogen economy come to a grand total of between €411 and €797 million. In addition to the wider losses of between €132 and €190 million as mentioned above. The additional market values and profit losses which will be suffered by the European economy and the impact to supply chains and products are discussed in more detail in section 8.4.

8.3 Emissions

In the non-use scenario, there would be no suitable alternative to Nafion™ membranes. The only reduction in emissions would be those associated with the loss in production of Nafion™. Since Nafion™ is manufactured outside of Europe, this falls outside of the scope of this assessment.

8.4 Value of downstream markets

8.4.1 Nafion™ in the hydrogen economy

8.4.1.1 MEA manufacturers

The non-use scenario defined above will result in the total loss of the membrane electrode assembly manufacturing market within Europe. MEA manufacturers supplying water electrolysis equipment manufacturers and hydrogen fuel cell producers are wholly dependent on access to Nafion™ IXM and as such a non-use scenario which removes this access will destroy the European industry and result in substantial economic losses for the European economy. The closure of the MEA market within Europe will result in the loss of over €3.6 billion in revenue over the course of the assessment period which will cause **the European economy to suffer losses in the region of over €230 million in lost profits** (see section 7.4.3.1 for calculations).

8.4.1.2 Water electrolysis equipment manufacturers

Due to the lack of data available for electrolysis equipment specific to water electrolysis for hydrogen generation no revenue and profit predictions have been possible. The RPA study team have therefore been unable to estimate the level of economic cost to the European economy resulting from a non-use scenario. However, given the market demand for high quality products, the technical function of Nafion™ IXM and lack of suitable alternatives, the RPA study is confident in the belief that under a non-use scenario the PEM water electrolysis equipment manufacture market would be completely crippled and incur 100% losses.

8.4.1.3 Hydrogen fuel cell manufacturers

Without access to Nafion™ IXM and MEA's it will become impossible for proton exchange membrane-based fuel cells to be manufactured within Europe. Such an event will result in the total closure of this type of fuel cell manufacturing industry with Europe. **This will cause the European economy to suffer economic losses in the region of over €334 million in lost profits** resulting from the total loss of revenue in Europe worth over €3.5 billion (see section 7.4.3.3 for calculations).

8.5 Health and environmental impacts (cost/benefits)

8.5.1 Health impacts

Based on the information available and since there is no production within the EU of Nafion™, health hazards are not of concern. Therefore, the health impacts under a continued use scenario have not been calculated, thus no health impacts are expected under a non-use scenario.

8.5.2 Environmental impacts

Based on the information available to date, the environmental concerns for Nafion™ relate to its persistency. Therefore, the environmental impacts under a continued use scenario have not been calculated, thus no environmental impacts relating to the non-manufacture of Nafion™ are expected also under a non-use scenario.

8.6 Unemployment

8.6.1 Chemours APM

As previously outlined in Section 7.6 by 2035, when a potential restriction may be adopted, there will be a total of 629 full time equivalent (FTE) employees employed because of Chemours APMs fluoropolymer operations within the EU. These employees are located across Europe at several sites and during consultation with APM it was disclosed that all these staff would face redundancy in the event of a PFAS restriction under REACH coming into effect. The SEAC guidance for assessing the cost and impact of unemployment is based on calculating the social cost of unemployment. This social cost is calculated according to the multiplication of the number of the employees who will lose their jobs, their average salary, and a ratio of social cost per job lost as calculated in Dubourg's (2016) paper. Table 8-1 presents this information and displays the calculated social cost of unemployment which will be suffered, due to a PFAS restriction, by the European economy broken down by each separate Member State which will be affected. It should be noted that the figures presented in the final total social cost column have all been rounded to three significant figures for clarity.

Table 8-1: Chemours APM Social Cost of Unemployment

Country	Number of Employees (FTE)	Average Salary (€)	Portion of workers being made redundant	Dubourg ratio of social cost per job lost	Total social cost of unemployment (€)
Netherlands	464.9	70,000	100%	2.35	76,500,000
Belgium	76.2	70,000	100%	3.03	16,200,000
France	66.3	70,000	100%	3.17	14,700,000
Spain	15	70,000	100%	2.80	2,940,000
Germany	5.7	70,000	100%	2.60	1,040,000
Denmark	1	70,000	100%	1.75	123,000
Source: APM personal communication 2022 and RPA study team analysis					

Table 8-2: Chemours APM Social Cost of Unemployment – new social cost ratios

Country	Number of Employees (FTE)	Average Salary (€)	Portion of workers being made redundant	Dubourg ratio of social cost per job lost	Total social cost of unemployment (€)
Netherlands	464.9	70,000	100%	3.16	103,000,000
Belgium	76.2	70,000	100%	3.86	20,600,000
France	66.3	70,000	100%	3.43	15,900,000
Spain	15	70,000	100%	3.83	4,020,000
Germany	5.7	70,000	100%	3.33	1,330,000
Denmark	1	70,000	100%	2.07	145,000
Source: APM personal communication 2022 and RPA study team analysis					

The unemployment generated from **cessation of Chemours APMs operations will generate total social costs in the order of over €111 million for the European economy under original social cost ratios and €145 million under new social cost ratios**. This is a considerable cost for the economy to suffer on top of the losses of output and profits from APM as outlined in previous sections. Not only that but some European nations will be more adversely affected than others. Member states such as Germany and Denmark will not see significant levels of unemployment with only 5.7 people and 1 person being made unemployed respectively. These low numbers of unemployment and low social costs will likely be able to be easily absorb by their respective economies and local communities. The Netherlands however will suffer much greater impacts because of a potential PFAS restriction. Most of the APM staff on payroll are positioned within the Netherlands and losing 465 employees on an average wage of €70,000 will produce social costs of €76.5 million for the Dutch economy. These are heavy losses to incur and such a high quantity of people losing their jobs from a single site closing will also have resounding local implications. A high concentration of unemployment occurring at the Dordrecht site will most likely see economic scaring occur throughout the local economy as the level of consumption falls and wages are no longer paid, which will result in a second wave of unemployment. Substantial effort would need to be made at the macro level to prevent a substantial negative multiplier effect taking hold on unemployment in the region.

8.6.2 Nafion™ in the hydrogen economy

As stated in section **Error! Reference source not found.**; due to the low response rate to the RPA consultation phase and the amalgamated nature and lack of public data; with regards to the number of enterprises and employees within the in-scope supply chains the level of employment has been incalculable. Consequently, the level of unemployment is also impossible to calculate based on the information available to the RPA study team. While an estimate to the figure and the social costs Europe would incur cannot be arrived at the RPA study team has sufficient information from consultation and desk research that a non-use scenario would mostly produce an unemployment rate within this sector of 100%.

8.7 Innovation and investment losses

8.7.1 Chemours APM

As referenced in section, 7.7 APM currently make substantial investments each year of €40.7 million into the development of their fluoropolymer businesses efficiency and into alternatives. However, given that the entire product portfolio of the APM division is fluoropolymers, a restriction would create an environment where all R&D activities within Europe conducted by APM would cease and investments would be moved to other regions. Therefore, reducing the annual level of investment made by APM into Europe for R&D to zero with the changes compared to the continued use scenario over the assessment period is presented in Table 8-3.

Table 8-3: Discounted annual R&D spending lost under a non-use scenario

Year	Total PFAS R&D (€)	Operational R&D (€)	Alternatives R&D (€)
2026	-33,400,000	-22,600,000	-10,800,000
2027	-32,100,000	-21,800,000	-10,400,000
2028	-30,900,000	-20,900,000	- 9,970,000
2029	-29,700,000	-20,100,000	- 9,580,000
2030	-28,600,000	-19,300,000	- 9,220,000
2031	-27,500,000	-18,600,000	-8,860,000
2032	- 26,400,000	-17,900,000	- 8,520,000
2033	-25,400,000	-17,200,000	- 8,190,000
2034	-24,400,000	-16,500,000	-7,880,000
2035	-23,500,000	-15,900,000	-7,570,000
Assessment period total	-281,900,000	-190,800,000	-90,990,000
Source: RPA study team analysis			

Europe would therefore lose out on over €281 million in investment and capital expenditure from APM as a direct result of a restriction being placed on PFAS within the EU. While this figure in itself is a substantial amount of investment to lose over the course of the investment period there is a wider issue generated with regards to research and development. This being the possible timeframes being faced by the impacted Nafion™ IXM industry to develop and implement new materials and practices.

Under a total restriction scenario and with no derogation being granted for PFAS to be used within the semiconductor industry the EU27 will see the total withdraw of the industry from the bloc. This will mean even further substantial losses of R&D investment related to both PFAS and semiconductor technologies being lost from Europe but would also leave the bloc without access to semiconductors. At the same time while these investments will be lost, the time scale that will be required to reinvent semiconductor technology so that it does not require fluoropolymers could take between 40 and 50 years, provided alternatives were viable. Therefore, in terms of research and development of fluoropolymers within the semiconductor industry it is not viable for PFAS to be banned and then invest in alternatives given the length of the lead time required to develop and implement new semiconductor production technology.

8.7.2 Downstream user investment losses

8.7.2.1 MEA manufacturers

Since Nafion™ is a material which is intrinsic to the manufacture of MEAs and no alternatives are available, the non-use scenario would result in the relocation of MEA manufacturing companies outside of the EU. Companies for which relocation would not be economically viable would close business. Business closure would result in the losses of vast investments made into developing high efficiency MEAs. All R&D investments made in researching alternative membrane materials has so far not been commercially successful and thus these investments would be lost. In addition, R&D into developing catalyst systems for fuel cells and electrolysers would also be lost as an indirect effect of the PFAS ban. Relocation of the companies outside of the EU would be associated with significant costs of building new manufacturing plants and hiring new skilled employees.

8.7.2.2 Water electrolysis equipment manufacturers

While the production of hydrogen will still be possible under a PFAS non-use scenario (either through fossil fuel methods or by alternative electrolysis), the PEMWE industry is currently set to overtake the market by a large majority in 2030. If the use of Nafion™ is restricted, the investments made to develop the WE technology into the efficient, low cost, low footprint, long lasting state of the art as it currently stands will be lost.

8.7.2.3 Hydrogen fuel cell manufacturers

In the event of a ban on the use of Nafion™ in the EU, MEA, stack and module manufacturers stated that their businesses would have to relocate outside of the EU. Those companies for which relocation would be impossible due to lack of capital stated that their business would close. It is clear that business closure would be a large loss in terms of investment in the specialist equipment used in the manufacture of these devices, as well as the investment lost from years of dedicated research into the commercial viability and implementation of fuel cell and water electrolysis technologies into the EU hydrogen market.

8.8 Wider implications: European strategic goals, consumers, and end-users

Throughout this report, it is clear that Nafion™ is intrinsic to the hydrogen economy in its current state. The availability and use of Nafion™ has allowed the development of lighter weight, low maintenance, robust fuel cell and water electrolyser technologies. As a result of these developments, the EU has been able to set out hydrogen use and production strategies which are in line with the **EU Green Deal** such as the **Clean Hydrogen Partnership** and **REPowerEU**. These strategies set out ambitious, short-term goals which drastically increase hydrogen production, infrastructure and aim to reduce CO_2 emissions and eliminate the EU's dependence on Russian oil and gas by 2027.

REPowerEU, published in May 2022, has drastically increased the EU's 2030 renewable hydrogen production and importation goals from its target proposed in the revised Renewable Energy Directive (2021) from 5.6 million tonnes of produced and imported renewable hydrogen combined, to 10 million tonnes *each* of produced renewable hydrogen and imported renewable hydrogen.

The framework for the hydrogen strategies is underpinned by recent advances in water electrolysis and fuel cell technology which would not be possible without Nafion™.

If a restriction on the manufacture and use of PFAS substances were to prevent Nafion™ membranes and dispersions being used in the EU, the production of electrolytic low-carbon hydrogen would be limited to the outdated and low-capacity technologies such as alkaline water electrolysers as discussed in section 6.

It is clear, that with no alternative membrane materials that are technically capable of meeting the functionality requirements of Nafion™ within PEMFCs and PEMWEs, a ban on the use of fluoropolymers in these technologies would severely reduce their contribution to the EU hydrogen strategy goals.

With the current price of fossil fuels increasing there has been more of a focus than ever to develop EU and country specific power sources which do not rely heavily on importation. Since the presence of fossil fuels within the Earth's crust is geographically uneven, it is impossible to foresee a paradigm where fossil fuels play a part in this decentralised energy economy. Renewable energy such as solar and wind power, however, is available to almost all areas of the world, if they can install the required infrastructure to capture.

8.9 Summary

The non-use scenario established for the purpose of this assessment is a total ban on the import, manufacture and use of all PFAS substances within the EU, including articles containing PFAS. This is the most restrictive scenario and provides a worst-case scenario. Due to the way Nafion™ IXM is used, a limit in formulation concentrations would also result in a *de-facto* ban.

The continued use and non-use scenarios have been compared based on a restriction timeline starting in 2025 with the effects not being felt until the start of 2026 and the assessment timeframe extending to the end of 2035. The assessment period has been chosen to reflect a potential date by when alternatives could be commercially available, however it is recognised that for the hydrogen economy this period may be much longer.

Under a non-use scenario all the markets within scope of this SEA would be lost from the European economy due to a lack of currently viable alternatives for these markets to switch to. The economic impact of this would be the loss of between €411 and €797 million in profits from Chemours APM, over €230 million in profit lost from MEA manufacturers and over €334 million in lost profits from fuel cell manufacturers. The total losses experienced across Europe will be much higher than this once profits from water electrolysis manufacturers are accounted for. Therefore, the non-use scenario will result in minimum economic losses to the European economy of between €976 million and €1.4 billion.

The non-use scenario will also result in unemployment across the EU. Chemours APM ceasing their fluoropolymer operations will result in 629 Full Time Equivalent (FTE) individuals losing their job with a social cost to Europe of between €111 and €145 million depending on the original and alternative Dubourg social cost ratios used. Additional unemployment will be felt throughout the hydrogen economy supply chains, but due to lack of available data the level of employment cannot be estimated. Therefore, also the full level and cost of unemployment cannot be estimated at this time.

Nafion™ IXM is not manufactured within Europe and as such there are no emissions currently occurring within Europe and very few to no emissions are predicted to occur along the hydrogen economies supply chains. As a result of this the non-use scenario will not generate any reduction in emissions in Europe. In addition to this, given that Nafion™ IXM has no known health and environmental hazards, there are no associated health and environmental benefits under a non-use scenario either.

Under the non-use scenario all current R&D spending related to PFAS, and the hydrogen economy will cease. Therefore, all current and future R&D plans of Chemours APM will be cancelled, which equates to €91 million, set to be spent on PFAS alternatives, no longer being invested in Europe. In addition to this an additional €191 million of operational R&D spending from APM will no longer occur as well as operation R&D spending from downstream users which will also be lost.

As well as incurring substantial economic losses, some of Europe's most ambitious and strategic political and economic objectives will be difficult to achieve under the non-use scenario. Policies such as the European Green Deal will be able to continue under the non-use scenario, but it will be severely hampered with the loss of the hydrogen economy from Europe. Other policies such as REPowerEU and the European hydrogen strategy will be impossible to achieve without access to materials such as Nafion™ IXM which will allow the hydrogen economy to assist in the decarbonisation of Europe.

9 Conclusions

This socio-economic analysis has looked to assess and value the benefits and costs to the European economy and society under a continued and non-use scenario regarding the importation and use of Nafion™ IXM supplied by the Advanced Performance Materials (APM) division of The Chemours Company. The sectors analysed are the European operations of Chemours APM and the hydrogen economy, consisting of the green hydrogen production and fuel cell manufacturing supply chains. For the actors in each of these supply chains and for APM's, the RPA study team sought, where possible, to evaluate: the volume of product being manufactured/imported and sold, the revenue the market segment generates, profits earned on these revenues, the number of enterprises within the sector; the number of employees within the sector, the value of continued employment, the social cost of unemployment, levels of research and development, potential health risks and savings, levels of emissions, and possible environmental costs while also considering impacts to existing and future EU polices and European consumers.

The continued use and non-use scenarios of this assessment consider the period from 2026-2035 to maintain comparability between both scenarios while also accounting for the likely period it would take for new alternatives and products to enter the market after a potential restriction may have come into force. **Over this period the total profits that were estimated from the use of Chemours APM products have been predicted at between €976 million and €1.4 billion with the total losses over the same assessment period estimated also at between €976 million and €1.4 billion.** Under the continued use and non-use scenario the benefits of employment and cost of unemployment cannot currently be estimated based on available data. The widespread sale and use of Nafion™ IXM and Nafion™ IXM products means all Member States of the European Union are impacted by these supply chains. All Member States can share in the financial and social benefits under the continued use scenario and similarly all Member States will suffer losses both financially and socially under the non-use scenario.

The positive continued use impacts and negative non-use impacts of Nafion™ IXM supplied by Chemours APM go beyond financial and employment. They effects are linked to several vital European security, social and environmental policies. Nafion™ IXM supplied by APM is a crucial component of vital societal functions, both for governments and citizens alike. Under a continued use scenario, it enables the ambitious European policies to become achievable, while under the non-use scenario the targets and policies will become much more challenging to achieve.

The methods applied in this report are not without limitation and a certain level of assumptions and uncertainties. One area of ambiguity is the time at which many of these assessments were made was at a time before the global and European economy begun to suffer with rising inflation and international crises. A global or European economic slowdown may result in the benefits and the costs presented in this assessment to be overestimated, however, these variances do not diminish the underlying findings of this assessment with regards to how vital Teflon™ PFA is to the supply chains within the scope of this assessment. In short, the figures and findings of the above assessment indicate that Europe is substantially better off, financially, and socially, under a continued use scenario than under a non-use scenario provided by a restriction.

The full list of findings covered by this assessment can be found in the tables below. The tables also present the scale of the benefits and or costs of each area of discovery for both the continued use and non-use scenario with the differences and impacts discussed alongside them.

Table 9-1: Continued use vs Non-use scenario Cost/Benefit summary – Chemours APM			
Impact areas	**Continued-use scenario**	**Non-use scenario**	**Difference**
Substance in scope	Nafion™ IXM (CAS: 31175-20-9)	None	Chemours APM would cease their European activities under a non-use scenario resulting in no products being supplied.
Volumes	2,198-2,931 tonnes (membranes) 93-140 tonnes (dispersions)	0	Cessation of business activities will result in a total prevention of all tonnes of Nafion™ IXM from being imported into Europe.
Revenues	€472-832 million (membranes) €26.3-134 million (dispersions)	€0	Cessation of business activities under non-use will result in total loss of all revenues.
Profits	€389-687 million (membranes) €21.7-110 million (dispersions)	€0	Cessation of business activities under non-use will result in total loss of all profits.
Emissions	0	0	No European based manufacturing results in 0 emissions under continued use and 0 emission reductions under non-use.
Health Impacts	0	0	Nafion™ IXM has no known hazards to harmful to human health, resulting in no human health costs under continued use and no health savings under non-use.
Environmental Impacts	0	0	Nafion™ IXM does not degrade during normal conditions of use, nor over time and is not PBT. It is persistent and environmental impacts are determined based on emissions, see above.
Employment	629 persons employed >€284 million employment value	629 persons unemployed €111 million - €145 million social costs	Cessation of business activities results in total loss of employment preventing employment benefits being experienced and instead incurs social costs of between €111 to €145 million.
Innovation	€281 million (total) €91 million (alternatives) €190 million (operational)	0	Total assessment period R&D spending of €281 million will no longer proceed due to no business portfolio being present to fund research projects.
EU policies	EU Green Deal EU hydrogen strategy European clean hydrogen alliance REPowerEU	EU Green Deal	Under a non-use scenario only the Green Deal will continue to be achievable albeit very severely hampered, all other strategic objectives will be unachievable under a non-use scenario.

Table 9-2: Continued use vs Non-use scenario Cost/Benefit summary – Downstream impact assessment			
Impact areas	**Continued-use scenario**	**Non-use scenario**	**Difference**
Products in scope	Membrane Electrode Assemblies (MEA) Polymer electrolyte membrane water electrolysis equipment Polymer electrolyte membrane fuel cells Heavy-duty fuel cell vehicle	None	All downstream users would cease their European activities under a non-use scenario resulting in no products being supplied.
Volumes	Unknown volumes of MEA's, electrolysis equipment, fuel cells and hydrogen vehicles	0	Cessation of business activities will result in a total prevention of all products from being manufactured and supplied in Europe.
Revenues	>€3.6 billion MEA revenues >€3.5 billion fuel cell revenues	€0	Cessation of business activities under non-use will result in total loss of all revenues.
Profits	>€230 million MEA profits >€334 million fuel cell profits	€0	Cessation of business activities under non-use will result in total loss of all profits.
Emissions	0	0	Nafion™ IXM is not emitted during the manufacturing stage of these products and no emissions will occur under a non-use scenario and emissions from legacy products has not been assessed.
Health Impacts	0	0	Nafion™ IXM is not hazardous. No products pose human health risks resulting in no health costs under continued use and no health savings under non-use.
Environmental Impacts	0	0	Nafion™ IXM has no environmental hazards. It is persistent and environmental impacts are determined based on emissions. In these end products negligible emissions are assumed therefore there are no environmental costs under continued use and no environmental savings under non-use.
Employment	Unknown	Unknown	Due to low consultation response rate and poor publicly available data employment and

Table 9-2: Continued use vs Non-use scenario Cost/Benefit summary – Downstream impact assessment			
Impact areas	**Continued-use scenario**	**Non-use scenario**	**Difference**
			unemployment impacts cannot be estimated.
Innovation	Unknown level of operational R&D expenditure	0	Due to lack of consultation responses current levels of operational R&D being spent by downstream users cannot be estimated but all R&D will cease under the non-use scenario.
EU policies	EU Green Deal EU hydrogen strategy European clean hydrogen alliance REPowerEU	EU Green Deal	Under a non-use scenario only the Green Deal will continue to be achievable albeit very severely hampered, all other strategic objectives will be unachievable under a non-use scenario.

Annex 1 Uncertainties and assumptions

This section presents an overview of the limitations and uncertainties of this study and considers their potential impact on the conclusions. Table A1-9-3 provides a summarised overview of each element and assesses their significance for the results of this study.

Table A1-9-3: Uncertainties and limitations			
Uncertainty and Limitation	Explanation	Under (-) or over (+) estimate	
		Cost	Benefits
Number of workers /companies	The number of enterprises with exposure and the number of exposed workers is challenging to calculate accurately. The number of workers is the primary determinant of the benefits and the number of companies the primary determinant of the costs. Both are related. The costs and benefits modelled under the use and non-use scenario may therefore be under- or overestimated.	++/--	++/--
Discount rate	The estimates in this report have all been modelled using a static discount rate of 4%. A declining discount rate allocates more weight to costs and benefits that occur after 20 years. Although the costs and benefits increase (due to the lower discounting effect), the cost-benefit ratio does not change. This further shows that the costs and benefits are generally equally distributed over time.	-/+	-/+
Positive bias in reported data	It is possible that there is some self-selection among companies that participated in the consultation for this study or provided data for the surveys of the industry associations. Worst-performing companies are less likely to be aware of PFAS in their products and be willing to contribute to the study. This may underestimate both costs and benefits and has not been further assessed.	-	-
Growth rates	The growth rates for Chemours APM operations and that of their downstream users were made and supplied to the RPA study team at a time before inflation begun to greatly accelerate. Since international crises have caused inflation to increase, spending to decline and economies to slow there is a high potential for the stated growth rates in this SEA to be above what will truly be experienced in the short term. This will likely only apply to the short term however with longer term projections likely to be unaffected. Slower true growth rates due to international economic issues may mean some of the short-term estimates within this SEA are unintentionally overestimated. The scale of this overestimation is hard to determine as this highly dependent on the scale and severity with which issues such as inflation and economic slowdown in Europe reach.	+?	+?
Profit margins of downstream users	The profit margins that have been applied to downstream users such as Li-ion battery	+/-	+/-

Table A1-9-3: Uncertainties and limitations			
Uncertainty and Limitation	Explanation	Under (-) or over (+) estimate	
		Cost	Benefits
	manufacturers are amalgamated industry average operating margins extracted from Eurostat. Given that these estimations account for many businesses, substances, and products out of scope of this SEA there is potential for estimates to be under or overestimated. In specific instances the above report has highlighted where it is believed underestimations or overestimations have been made.		
Tax contributions of employees	All tax calculations have been estimated on a "most expensive" scenario whereby the highest possible tax bill for an individual has been estimated by assuming all individuals are unmarried and have no dependents. The tax income per person is therefore likely to be an overestimation of the true tax bills most of these individuals would face and subsequently national tax receipts would be lower. However, the model the RPA study team have designed does not use multipliers and as such putting extra income under tax receipts or disposable income results in the same final employment benefit figure. Therefore, while tax receipts are overestimated the final benefit is not.	NA	+
Chemours and sector employment contributions	Once again however it should be noted this value is likely to be considerably higher as these figures will be subject to government spending, money, and consumption multipliers but these multipliers cannot currently be accurately estimated.	NA	--
Government spending multiplier and a consumption multiplier	All benefits of employment will have been underestimated due to no government spending or consumption multipliers being applied. These would naturally occur within an economic system and thus will grow the scale of the returns provided by employment but with them not being applied in the model of this SEA the presented benefits will be underestimated by large amounts.	NA	---
Source: RPA Study Team analysis			

Annex 2 Consultation Response Statistics

The number of consultation responses and interviews for the APM division are summarised within this Annex, a summary of responses can be seen in the table below. Questionnaires were constructed to target specific information for each player in the supply chain.

Due to the crossover in the supply chain, i.e., some MEA manufacturers may also manufacture stacks, some stack manufacturers also manufacture modules etc., a single survey was developed to fully encompass the industry. RPA invited all companies to semi-structured interviews, unless they declined to participate in the survey, and conducted interviews with six companies. The survey was sent in April 2022, and it was preceded by a workshop introducing the scope and purpose of the survey. Interviews were conducted in Q3 2022.

The table below presents a summary of all surveys and interviews. N.B. due to the supply chain overlap, the total number of companies consulted is lower than the sum of actors in the supply chain.

Table A2-9-4: Consultation responses summary

	Surveys	Interviews
Total surveys/interview invitations sent	***14***	**7**
Water Electrolysis Membrane Electrode Assembly producer (WE-MEA)	1	1
Water Electrolysis Stack and Module Producers (WE-SMP)	2	2
Heavy-Duty Vehicles Fuel Cell producers	0	0
Hydrogen Fuel Cell Stack and Module Producers (SMMFC)	3	1
Hydrogen Fuel Cell Membrane Electrode Assembly Producers (FC-MEA)	0	1*
Total surveys/interviews conducted	***6***	***6***

Source: RPA study team analysis
Notes
(*)The company interviewed and noted as a hydrogen fuel cell membrane electrode assembly producer is also a water electrolysis membrane electrode assembly producer.

The topic has been important within the affected industries and corresponding industry associations. There have been several concurrent surveys running, which the study team believes hampered efforts in obtaining further data.

Risk & Policy Analysts Limited
Suite C, 2nd floor, The Atrium, St Georges Street
Norwich, Norfolk, NR3 1AB, United Kingdom

Tel: [redacted]
E-mail: [redacted]@rpaltd.co.uk
Website: www.rpaltd.co.uk

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