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Technical Report covering fluoropolymers at end-of-life

Final report

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The regulatory status of PFAS is continuing to evolve, and the scientific community is generating additional data regarding PFAS properties and potential impact. The conclusions of this report are therefore subject to reassessment as regulations change and additional scientific information regarding PFAS becomes available.

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Contents

Abbreviation List

Abbreviation	Full term
AFFF	Aqueous Film-Forming Foam
ASR	Automotive Shredder Residue
BAT	Best Available Techniques
BREF	Best Available Techniques Reference Document
CAPEX	Capital Expenditure
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CEWEP	Confederation of European Waste-to-Energy Plants
CFC	Chlorofluorocarbon
CFC-11	Chlorofluorocarbon-11
CO2e	Carbon dioxide equivalent
D10	Disposal operation code for incineration on land (EU Waste Framework Directive)
DPP	Digital Product Passport
ECHA	European Chemicals Agency
ECTFE	Ethylene Chlorotrifluoroethylene
ELV	End-of-Life Vehicle
EO	Electrooxidation
EoL	End of Life
EPA	Environmental Protection Agency
EPR	Extended Producer Responsibility
ESPs	electrostatic precipitators
ETFE	Ethylene Tetrafluoroethylene
EU	European Union
EU-27	European Union 27
FEPM	Tetrafluoroethylene propylene elastomer
FFKM	Perfluoroelastomer
FKM	Fluoroelastomer
FP	Fluoropolymer
FPRA	Polymer Processing and Recycling Aid
FPs	Fluoropolymers
FTIR	Fourier Transform Infrared (spectroscopy)
GC-MS	gas chromatography/mass spectrometry

Abbreviation	Full term
GKS	Gemeinschaftskraftwerk Schweinfurt
GWP	Global Warming Potential
HALT	Hydrothermal Alkaline Treatment
HCFC	Hydrochlorofluorocarbon
HCFC-22	hydrochlorofluorocarbon-22
HFP	Hexafluoropropylene
HFPO-DA	Hexafluoropropylene oxide dimer acid
IPCC	Intergovernmental Panel on Climate Change
ISWA	International Solid Waste Association
IX	Ion Exchange
KIT	Karlsruhe Institute of Technology
kt	Kilotonne
L/S	Liquid-to-Solid ratio
LIBS	Laser-Induced Breakdown Spectroscopy
MIR	Mid-Infrared (spectroscopy)
MSW	Municipal Solid Waste
NIR	Near-Infrared (spectroscopy)
OECD	Organisation for Economic Co-operation and Development
OPEX	Operational Expenditure
OTM-45	Other Test Method 45
OTM-50	Other Test Method 50
PA	Polyamide
PFA	Perfluoroalkoxy Alkane
PFAS	Per- and Polyfluoroalkyl Substances
PFBA	Perfluorobutanoic Acid
PFCA	Perfluorocarboxylic Acid
PFHxA	Perfluorohexanoic Acid
PFOA	Perfluorooctanoic Acid
PICs	Products of incomplete combustion
PMMA	Polymethyl Methacrylate
POM	Polyoxymethylene
POPs	Persistent Organic Pollutants
PP	Polypropylene
PTFE	Polytetrafluoroethylene

Abbreviation	Full term
PVDF	Polyvinylidene Fluoride
PVF	Polyvinyl Fluoride
R1	Energy-efficiency classification for waste incineration
RAC	Risk Assessment Committee (ECHA)
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RIVM	National Institute for Public Health and the Environment, The Netherlands
RO	Reverse Osmosis
SCFP	Side-Chain Fluorinated Polymer
SCR	Selective catalytic reduction
SCWO	Supercritical Water Oxidation
SEAC	Socio-Economic Analysis Committee (ECHA)
SHF	Shredder Heavy Fraction
SLF	Shredder Light Fraction
TFA	Trifluoroacetic Acid
TFE	Tetrafluoroethylene
THV	Terpolymer of TFE, HFP and VDF
U.S.	United States
UNEP	United Nations Environment Programme
USA	United States of America
VDF	Vinylidene Fluoride
WAC	Waste Acceptance Criteria
WEEE	Waste Electrical and Electronic Equipment
WTE	Waste-to-Energy
XAD	crosslinked polystyrene-divinylbenzene resin

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Abstract

This report examines the end-of-life management of fluoropolymers in Europe, with particular attention to their position in the waste hierarchy, their occurrence in waste streams, and the technical characteristics that influence their treatment. Fluoropolymers are a specific subgroup of polymeric PFAS and are mainly used in demanding applications where high resistance to chemicals, heat, weathering, pressure and mechanical stress is required. In many cases, they are used as liners, seals, gaskets, coatings, membranes or insulation layers within larger products rather than as stand-alone materials. Waste prevention is central to the EU waste hierarchy and fluoropolymers can contribute to prevention primarily through the fact that small linings, seals, gaskets or coatings can protect much larger components and extend service life and thus reducing replacement-related waste. This "leverage effect" means that a relatively small fluoropolymer mass can enable a large reduction in waste by avoiding premature failure of the host product.

A central finding is that at end of life, fluoropolymers rarely occur as separate waste streams. Instead, they usually follow the waste route of the host product in which they are embedded. In 2020, around 23,500 tonnes of fluoropolymer containing waste were collected in the EU, representing less than 0.01 percent of total waste by mass.

The report shows that current end-of-life management is dominated by hazardous waste incineration and municipal waste to energy combustion, while landfill, and thermal destruction during metal recycling play minor roles and dedicated recycling remains limited. Available evidence indicates that under regulated incineration conditions, fluoropolymers are largely mineralised, with fluorine captured mainly as inorganic fluoride salts in treatment residues. Measured emissions of water soluble PFAS and volatile fluorinated compounds are very low in the available full scale test data. Three measured volatile fluorinated compounds (CF_4 + C_2F_6 + CHF_3) are recognised greenhouse gases. However, the Climate Impact of the emissions of these three compounds are shown to be thousands of times less than the plant's CO_2 emission concentration (assuming presence at the detection limits for non-detect values) under routine operating conditions. Generation of CF_4, at detectable levels, from municipal WTE combustion requires extreme conditions unrepresentative of typical municipal WTE plant operation and unrelated to end-of-life fluoropolymers in MSW.

Landfilling plays a smaller role and is subject to a strict EU control framework, although uncertainties remain regarding the potential contribution of fluoropolymer waste, if any, to PFAS detected in landfill leachate. Fluoropolymers are characterised by high molecular weight, low water solubility and strong carbon–fluorine bonds, which limit their mobility and result in a high degree of chemical and physical stability under typical use conditions (Améduri & Hori, 2023). For landfill conditions the body of evidence is limited, but available evidence indicates that fluoropolymers are resistant to biodegradation under aerobic and anaerobic conditions, are hydrolytically and photochemically stable, and are thermodynamically stable at temperatures far below those encountered in landfill environments (Henry et al., 2018; Ellis et al., 2001; Henry & Timmer, 2025). Recycling is technically feasible for certain fluoropolymers and clean production scrap, but post-consumer recycling is constrained by low volumes, complex product integration, contamination, limited sorting infrastructure, market barriers and regulatory uncertainty.

Executive summary

Fluoropolymers occupy a distinct and highly specialised position within both the broader polymer universe and the PFAS universe. Under established scientific and regulatory definitions, they categorised as polymeric PFAS. At the same time, they differ significantly from many other PFAS due to their high-molecular-weight, solid polymeric form, and use predominantly in durable applications, which results in material properties and use patterns that are fundamentally different from those of low-molecular weight PFAS.

From a polymer perspective, fluoropolymers are not typical commodity plastics. Unlike conventional polymers such as polyethylene or polypropylene, which are based mainly on hydrocarbon backbones, fluoropolymers are characterised by carbon backbones in which hydrogen atoms are partly or fully replaced by fluorine. This gives rise to the carbon–fluorine bond, one of the strongest bonds in organic chemistry. As a result, fluoropolymers show exceptional resistance to heat, chemicals, weathering and degradation. Many fluoropolymers also exhibit very low surface energy, which contributes to properties such as non-stick behaviour, chemical inertness and reliable long-term performance under demanding operating conditions.

These characteristics explain why fluoropolymers are used in applications where many other materials would fail, especially in applications requiring high durability and long service life. They are found in chemical processing equipment, wire and cable insulation, semiconductor manufacturing, automotive and aerospace components, energy technologies, and medical or industrial sealing systems. In most cases, however, fluoropolymers are not used as stand-alone bulk products. They are typically present as a liner, coating, membrane, seal, gasket, tube, film or insulation layer within a much larger and more complex product or installation.

This is highly relevant for end-of-life management because fluoropolymers are usually embedded in larger articles and often represent only a small share of the total product mass. As a result, they are rarely collected or treated as separate waste streams after use. Instead, they generally follow the waste stream of the main application in which they are used. For example, fluoropolymer-lined equipment may enter metal recycling or hazardous waste treatment, fluoropolymer-insulated cables typically follow WEEE, construction or automotive waste routes and fluoroelastomer seals usually remain in larger assemblies until shredding, metal recovery or thermal treatment. Their end-of-life profile is therefore shaped not only by intrinsic material properties, but also by product design, contamination, dismantling practice and the economics of waste sorting and recovery.

The report focuses on the fluoropolymers most frequently used in industry: **PTFE, FEP, PFA, ETFE, PVDF, FKM and FFKM**. These materials do not all behave in the same way. PTFE, for example, is not melt-processable and is often used in sintered forms, whereas FEP, PFA, ETFE and PVDF are melt-processable fluorothermoplastics that can be processed by more conventional thermoplastic methods. FKM and FFKM belong to the fluoroelastomer family and most of them are crosslinked in commercial use, which limits reprocessing options. These differences are important because they influence where the material appears in products, how it enters waste streams, and which recycling or disposal routes are technically feasible.

Against this background, the report examines fluoropolymers through the lens of the EU waste hierarchy. It starts from waste prevention, then analyses end-of-life flows and the waste streams in which fluoropolymers occur and finally reviews the main waste management options. A central message from the introduction is that fluoropolymers cannot be understood as a uniform waste category. Their end-of-life management depends on the specific polymer type, whether the material is thermoplastic or crosslinked, whether it is present as a separate part or integrated into a complex article, and whether clean and identifiable material streams exist. Any technically sound policy discussion therefore needs to reflect both the common features and the important differences within the fluoropolymer group.

Waste prevention

Waste prevention is the top priority in the EU waste hierarchy. For fluoropolymers, the main prevention benefit comes from their durability in demanding conditions such as exposure to aggressive chemicals, high or fluctuating temperatures, pressure, mechanical stress and weathering.

Across sectors such as chemical processing, transport, electronics, energy, construction and medical applications, fluoropolymers are often used as liners, seals, gaskets, coatings, membranes or hose layers, rather than as the main product material. Even in small quantities, these parts can protect larger components against corrosion, leakage, wear or thermal degradation and thereby significantly extend their service life.

Stakeholder feedback in this project indicates that fluoropolymers can significantly extend service life, in some cases by three to ten times, depending on the application and operating conditions. Examples include lined pipes and fittings in chemical processing, seals in pumps and compressors, fuel system hoses, architectural fabrics and protective coatings.

A key concept discussed in the report is the so-called "leverage effect", whereby a relatively small mass of fluoropolymer enables a disproportionately large extension of service life for a much larger component or system. Thin fluoropolymer liners, seals, or gaskets can prevent corrosion, chemical attack, or leakage, thereby avoiding premature failure of pipes, pumps, or other assemblies.

Waste reduction through longer replacement cycles

Longer service life directly translates into waste reduction. If components last longer, fewer replacements are required over a given period, resulting in lower material demand, reduced manufacturing and transport activity, and less material entering the waste stream.

The report introduces an illustrative approach to estimate this effect through extended replacement cycles. For example, if a component lasts 15 years with a fluoropolymer solution instead of 5 years without it, fewer replacements are needed over the same period. Importantly, the waste avoided is often dominated by the larger protected component rather than the small fluoropolymer part itself, reflecting the leverage effect described above. Similar mechanisms apply to maintenance-related waste with longer intervals between repairs, recoating, or repainting reduce the consumption of materials, packaging, and removed material over the lifetime of a system, for example in construction applications.

At the same time, the evidence base remains limited. Much of the available information is derived from stakeholder feedback, case examples and qualitative literature, while direct public comparisons between identical applications with and without fluoropolymers are scarce. The examples in this chapter should therefore be seen as illustrative rather than representative, but they indicate that fluoropolymers can play an important role in waste prevention.

End-of Life landscape

End of life describes the point at which a product, component or piece of equipment can no longer be used for its intended purpose and is removed from service. At that stage, it becomes waste and enters a waste management route. For fluoropolymers, this stage is particularly important because their end-of-life profile is shaped not only by the material itself, but also by the type of product in which it is used, the way that product is collected and treated, and the technical feasibility of separating fluoropolymer parts from larger assemblies.

Based on the available data, fluoropolymer production and use in the EU are estimated to be in the range of about 40,000 to 52,000 tonnes per year in primary form (Wahlström et al., 2021; Wood, 2022). In 2020, around 23,500 tonnes of fluoropolymer containing waste were collected in the EU (Conversio Market & Strategy, 2023). This is a very small share of total EU waste by mass, below 0.01 %, and far below plastics overall. At the same time, the overall balance remains incomplete, because fluoropolymers contained in imported and exported articles such as electronics, transport equipment, textiles or cookware are not well captured in official statistics.

Available evidence indicates that fluoropolymers seldom occur at end-of-life as a separate waste stream, because they are usually embedded in products and it is often not either possible or manageable to separate the thin layers containing fluorinated polymers (Wahlström et al., 2021). In most applications, they are used as thin coatings, internal linings, cable insulation, membranes, seals, gaskets or other small components within complex products. As a result, they generally follow the end-of-life route of the host product rather than being removed and treated on their own. This is why the main fluoropolymer waste streams today are commercial and industrial waste, waste electrical and electronic equipment (WEEE), and end of life vehicles (ELV) (Conversio Market & Strategy, 2023).

Current end-of-life management is therefore dominated by disposal and destruction routes rather than by recycling. The largest share of collected fluoropolymer waste is estimated to be sent to hazardous waste incineration. Additional shares go to municipal waste to energy plants, landfill, and thermal destruction during metal recycling, while only a small proportion is currently recycled. Existing recycling activity is focused mainly on clean and relatively pure production scrap (Wahlström et al., 2021). By contrast, post-use fluoropolymer waste is usually mixed, contaminated or too difficult to separate, which makes material recovery much less common.

Stakeholder feedback confirms this overall picture. Respondents to a survey carried out in the scope of this project describe hazardous waste incineration as the most common route for many fluoropolymer containing products, especially where materials are contaminated, present only in small amounts, or integrated into complex systems. They also identify several barriers to wider recycling, including technical separation limits, contamination, lack of markets for secondary materials, and uncertainty about future regulatory treatment.

The report shows that fluoropolymers at end of life are characterised by low volumes, high dispersion across complex waste streams, and limited separate recovery. Their end-of-life route is usually determined less by the fluoropolymer itself than by the larger product system in which it is embedded. This helps explain why incineration and thermal destruction currently dominate, while recycling remains largely confined to selected upstream waste streams.

Hazardous waste incineration

Based on further differentiation of data from (Conversio Market & Strategy, 2023) hazardous waste incineration can currently be considered as the main end-of-life route for fluoropolymers in Europe, especially for industrial applications where fluoropolymer parts are removed from service together with contaminated equipment, seals, gaskets, tubing or liners. In these cases, fluoropolymers enter hazardous waste streams due to contamination arising from their use and service environment, rather than because the fluoropolymer material itself inherently requires hazardous waste management. As a result, these wastes are typically mixed with other hazardous industrial residues and managed in hazardous waste incinerators rather than separated for recycling.

European hazardous waste incinerators operate under strict regulatory requirements and use rotary kiln systems followed by a secondary combustion chamber. In practice, secondary combustion chamber temperatures are typically in the range of about 1050°C to 1300°C with a gas residence time of 2 seconds (Buekens, 2013; Hitachi Zosen Inova AG, 2024). These operating conditions are designed to ensure the effective destruction of hazardous organic materials.

For fluoropolymers, the expected combustion chemistry is well understood. Under incineration conditions, the polymer first decomposes into gaseous intermediates, which are then oxidised. In the presence of hydrogen sources, the dominant fluorinated product is expected to be hydrogen fluoride. This hydrogen fluoride is then controlled in the flue gas cleaning system, where alkaline reagents convert it into inorganic fluoride salts such as calcium fluoride or sodium fluoride collected with the solid residue.

Available full-scale testing supports this picture. Stack measurements at hazardous waste incinerators show very low emissions of water soluble PFAS, with a conservatively estimated

emission factor of less than 1 gram per tonne of fluoropolymer incinerated (for derivation see section 5.5.2.). This corresponds to a destruction efficiency greater than 99.9999 %.

For volatile fluorinated compounds, including recognised greenhouse gases such as CF_4 and C_2F_6, measured concentrations were also very low. Even when non-detect values are treated conservatively, their climate impact remains thousands of times lower than the climate impact associated with the incinerator's carbon dioxide emissions.

Hazardous waste incineration is the dominant and technically established end-of-life route for fluoropolymers in industrial hazardous waste streams. Based on both combustion chemistry and available stack testing, it leads predominantly to mineralisation and inorganic fluoride capture, while emissions of organic fluorinated compounds appear to be very low under regulated operating conditions. In addition to the peer-reviewed literature, further large-scale investigations are ongoing, including comprehensive test programmes at dedicated hazardous and thermal waste treatment facilities such as the GKS plant in Schweinfurt. Findings from these studies have been presented at scientific conferences and are expected to be published in the near future. As they provide a comprehensive and important source of information necessary for the discussion around end-of-life od fluoropolymers such pre-publication data have been integrated into this report together with available already published data.

Municipal waste-to-energy combustion

Municipal waste to energy combustion is also an important end-of-life route for fluoropolymers that are present in consumer waste and in mixed residual waste streams such as WEEE residues and automotive shredder residue. In 2020, around 22% of collected fluoropolymer waste, or about 5.15 kt (Conversio Market & Strategy, 2023), was estimated to flow to municipal waste to energy plants in Europe.

In practice, fluoropolymers reach these plants as minor components of larger waste streams rather than as separate fractions. They may be present in articles such as non-stick cookware, pipe sealing tape, cables, technical textiles, and small automotive parts. As a result, they are combusted together with municipal solid waste or mixed residual fractions from downstream treatment systems.

The dominant municipal waste to energy technology in Europe is moving grate combustion, which accounts for more than 90 % of design capacity. Although the regulatory minimum temperature is lower, actual combustion zone temperatures in these plants are typically well above 1100°C for around 2 seconds (The European Parliament and the Council of the European Union, 2010). These operating conditions are considered sufficient for the effective destruction of fluoropolymer decomposition products.

The expected chemistry is similar to that described for hazardous waste incineration. Fluoropolymers first decompose into gaseous intermediates, which are then oxidised. Because municipal solid waste contains abundant hydrogen sources, the dominant fluorinated product is expected to be hydrogen fluoride rather than persistent organic fluorinated compounds. This hydrogen fluoride is subsequently removed in flue gas cleaning and converted into inorganic fluoride salts such as calcium fluoride or sodium fluoride in the treatment residue.

Available stack testing supports this interpretation. Measured emissions of water soluble PFAS from full scale municipal waste to energy plants are very low, with conservatively estimated emission factors below 1 gram per tonne of fluoropolymer incinerated (for derivation see section 6.5.2). This corresponds to a destruction efficiency greater than 99.9999 %.

For volatile fluorinated compounds such as CF_4, C_2F_6 and CHF_3, measured concentrations under routine conditions were also very low. Their climate impact was found to be far smaller than the impact of the plant's carbon dioxide emissions. Moreover, elevated CF_4 formation was observed only under highly artificial test conditions involving strong spiking with concentrated fluorinated liquids and other organofluorine materials (Wohter et al., 2025; Wohter, Quicker, et al., 2026), which are not representative of normal fluoropolymer waste in municipal waste streams.

Municipal waste to energy combustion is a technically established end-of-life route for fluoropolymers in mixed municipal and residual waste streams. Under routine European operating conditions, the available evidence suggests that fluoropolymers are largely mineralised and that emissions of organic fluorinated compounds remain very low.

Landfilling

Only a minor share of fluoropolymer waste currently goes to landfill. In 2020, this was estimated at around 13 % of collected fluoropolymer waste, or about 3.09 kilotonnes (Conversio Market & Strategy, 2023). This share is expected to decline further over time, as EU waste policy discourages landfilling and gives priority to prevention, recovery and other treatment options.

Where fluoropolymer waste is landfilled, it usually does not occur as a separate waste stream. Instead, it is typically present in mixed waste from residential sources, electronics, end-of-life vehicles including shredder residues, and some commercial and industrial applications. Depending on the waste stream and its classification, such waste may be directed to landfills for non-hazardous or hazardous waste. In practice, most fluoropolymer containing waste sent to landfill is expected to go to non-hazardous landfills, provided that the applicable acceptance criteria are met.

The environmental discussion around landfilling focuses mainly on emissions, especially through landfill leachate, while air emissions are generally considered of lower relevance because the reaction conditions required for generating volatile compounds from fluoropolymers are difficult to reach in landfills. Fluoropolymers are characterised by high molecular weight, low water solubility and strong carbon–fluorine bonds, which limit their mobility and result in a high degree of chemical and physical stability under typical use conditions (Améduri & Hori, 2023). For landfill conditions the body of evidence is limited, but available evidence indicates that fluoropolymers are resistant to biodegradation under aerobic and anaerobic conditions, are hydrolytically and photochemically stable, and are thermodynamically stable at temperatures far below those encountered in landfill environments (Henry et al., 2018; Ellis et al., 2001; Henry & Timmer, 2025). Despite this high intrinsic stability, the current evidence does not allow a clear quantification of how much of the PFAS found in landfill leachate, if any, is directly attributable to fluoropolymers rather than to non-polymeric PFAS or other fluorinated and non-fluorinated materials present in the waste.

Metal Recycling

Fluoropolymers often reach end of life as part of metal products rather than as separate waste streams. Typical examples include non-stick cookware, lined pipes, coated fittings, cables, machinery and automotive parts. Where the main value of the product lies in the metal fraction, these items usually enter standard metal recycling routes instead of dedicated fluoropolymer treatment.

In 2020, metal recycling was estimated to account for about 11.5% of collected fluoropolymer waste, corresponding to roughly 2.7 kilotonnes. In these cases, fluoropolymers are typically not recovered as a material but are thermally destroyed during smelting while the metal fraction is recycled (Conversio Market & Strategy, 2023).

Before smelting, metal waste undergoes collection and pre-processing steps such as dismantling, shredding, sorting and separation. In some cases, polymer fractions such as cable insulation can be removed mechanically. However, many fluoropolymers are present as tightly bonded coatings, linings or small integrated parts that cannot be separated economically or technically. These fluoropolymer containing fractions therefore remain attached to the metal and enter steel, aluminium or copper recycling furnaces together with the scrap.

In these metallurgical processes, fluoropolymers are exposed to temperatures and gas phase conditions that are sufficient to destroy organic materials. Steel and copper recycling in particular involve very high temperatures, while even in aluminium recycling the waste gas temperatures are typically high enough for thermal destruction of fluoropolymer residues. Furnace systems and secondary treatment stages are designed to achieve complete oxidation of organic compounds in off

gases, and air pollution control systems such as lime injection, dry or wet scrubbing, and particulate filters are used to capture acidic and particulate emissions.

At the same time, the exact contribution of fluoropolymers to total fluorine related emissions from metal recycling is not well quantified. Emission reporting for metal furnaces includes components such as hydrogen fluoride and organic pollutants, but these data do not distinguish clearly between fluoropolymers and other possible fluorine sources such as fluxes, fuels or mixed waste inputs. No evidence was found that the typical fluoropolymer content in scrap causes specific metal quality problems. In general, quality concerns in metal recycling are linked mainly to metallic contaminants rather than to fluoropolymer residues.

Fluoropolymer recycling

Recycling is currently the least used end-of-life route for fluoropolymer containing waste. In principle, fluoropolymers can be recycled, and some routes are technically established. In practice, however, recycling is still focused mainly on clean pre-consumer waste such as production and processing scrap, while post-consumer recycling remains limited.

The main reason is not that fluoropolymer recycling is impossible as such, but that fluoropolymers occur only in very small amounts in most waste streams and are usually embedded in complex products. With a share of less than 0.01 % of total waste by weight, fluoropolymers are rarely present in quantities that make separate collection, identification and sorting attractive with current systems. As a result, most end-of-life fluoropolymer waste is not recycled but managed through municipal waste to energy combustion, hazardous waste incineration or landfill.

The recycling options differ between fluoropolymer types. Melt processable fluorothermoplastics can, in principle, be recycled in ways similar to other thermoplastics, especially where clean and homogeneous scrap is available. PTFE is more difficult because it is not melt-processable under conventional conditions, while crosslinked fluoroelastomers such as FKM cannot be remelted and therefore require other approaches. This means that the technical properties of the polymer strongly influence which recycling route is feasible.

For clean production scrap, primary mechanical recycling is already practised. Secondary recycling routes also exist, especially for PTFE, where the material is converted into micropowders used in applications such as coatings, lubricants, inks, plastics and elastomers. More advanced tertiary recycling or upcycling approaches can depolymerise fully fluorinated fluoropolymers such as PTFE, PFA and FEP into monomers like tetrafluoroethylene (TFE) and hexafluoropropylene (HFP), which can then be reused as feedstock.

These advanced routes are technically promising, but they also face important limitations. TFE is reactive, difficult to handle and subject to strict safety requirements, which makes commercial scale operation complex and costly. In addition, based on feedback from the stakeholder survey, there is currently no established market or efficient value chain in Europe for secondary fluoropolymer materials from post-consumer waste. The picture differs for the Asian market. In addition, many high-performance applications also require virgin grade material, which limits the market for recyclates.

Stakeholder feedback confirms that the main barriers are legal uncertainty, limited collection and sorting infrastructure, contamination, quality requirements and lack of transparency along the value chain. This makes decisions on waste management heavily dependent on third party contractors, local rules and costs.

1. Introduction

Key messages

- Fluoropolymers are part of the PFAS and the polymer universe
- Because of their chemical properties, they can be used in extreme conditions, in which most other polymers would fail
- The most common fluoropolymers differ in their properties, which results in different applications.
- Mostly only parts of broader applications are made of fluoropolymers, they line pipes and vessels to resist strong acids and oxidising media, insulate wires and cables in environments where a combination of high temperature, electrical performance and fire safety is essential or are found in seals, gaskets and membranes.
- This has a significant influence on their end-of-life management, as they are mostly not considered separately but follow the waste stream of the main application.
- End of life management also depends on their properties and can differ among different fluoropolymers.
- In many systems, small fluoropolymer parts (e.g. gaskets, liners, coatings) protect larger components (e.g. pipes, turbochargers). This creates a "leverage effect" where a small fluoropolymer share helps avoid the early replacement of much larger parts.

Fluoropolymers and their place in the PFAS universe

According to sources like Buck et al.(Buck et al., 2011) and the Organisation for Economic Co-operation and Development (OECD) (OECD, 2021), fluoropolymers can be classified as per- and polyfluoroalkyl Substances (PFASs) under certain definitions.

PFASs are a vast group of organic fluorine compounds that also include various pharmaceuticals and agrochemicals. They have attracted regulatory attention because certain PFAS are persistent in the environment, tend to accumulate in living organisms, and potentially degrade into persistent metabolites. Certain PFASs are also concerning because of their toxicity, bioaccumulation potential, and capacity for long-range environmental transport.

PFAS comprises non-polymeric and polymeric substances but also gases, liquids and solids (Henry & Timmer, 2025). Polymeric PFAS can further be split into fluoropolymers, perfluoropolyethers, and side chain fluorinated polymers (Buck et al., 2011; OECD, 2021).

Substance specific restrictions for PFAS

In the European Union, certain PFAS have been regulated through specific legislative measures such as the F-Gas Regulation and the Mobile Air Conditioning (MAC) Directive. Certain PFAS such as perfluorooctanesulfonic acid (PFOS), perfluorooctanoic acid (PFOA) and perfluorohexanesulfonic acid (PFHxS) are listed under Persistent Organic Pollutants (POPs) Regulation (EU) 2019/1021, which implements the Stockholm Convention and restricts their production, use, and release. Additionally, PFAS have been subject to the Regulation (EC) No 1907/2006 of the European Parliament and of the Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), which has played a key role in restricting substances like PFOA and related C8 compounds.

Following the restrictions on C8 chemistry, some industrial users shifted towards short-chain alternatives, such as C6 chemistry, which includes compounds like perfluorohexanoic acid (PFHxA). Germany submitted an Annex XV restriction dossier on PFHxA and its related substances in December 2019, and this process has now resulted in Regulation (EU) 2024/2462, adopted on 19 September 2024. The regulation introduces a new entry 79 in Annex XVII to REACH and restricts PFHxA, its salts and related substances in a wide range of uses, entering into force on 10 October 2024 and starting to apply from 2026 onwards. In parallel, long-chain perfluoroalkyl carboxylic acids with 9–14 carbon atoms (C9–C14 PFCAs) and their related substances are already restricted under entry 68 of Annex XVII, with the main provisions applying from 25 February 2023. After the adoption of C9–C21 long-chain PFCAs into Annex A (Elimination) at COP12 in 2025, the EU POPs Committee is considering their transfer from REACH (C9–C14) to the EU POPs Regulation (C9–C21).

So far, substance specific restrictions have not been envisaged for fluoropolymers.

Group restriction for PFAS

On 22 March 2023, the European Chemicals Agency (ECHA) published a proposal for a universal ban on approximately 10,000 PFAS substances, including fluoropolymers. The proposal aims to restrict the manufacture, marketing, and use of PFAS to minimise their risks to human health and the environment. Following the initial public consultation held from 22 March to 25 September 2023, the PFAS restriction process has advanced significantly. In August 2025, the dossier submitters published an updated background document, and ECHA later confirmed the timetable for the committees' assessment. As of March 2026, RAC has adopted its opinion and SEAC has issued its draft opinion, which is now subject to a further public consultation running until 25 May 2026. These regulatory actions on PFAS are expected to have significant impacts on the manufacture, importation, marketing, and use of fluoropolymers within the EU. The proposed scope covers non-polymeric (e.g., perfluoroalkyl carboxylic acids, perfluorocarbons) and polymeric PFAS (e.g., fluoropolymers, perfluoropolyethers) (Kemi, 2025).

As explained above, fluoropolymers are a specific and structurally distinct group within the broad PFAS group and even within the group of polymeric PFAS. Although their distinct physicochemical properties are well established, regulatory discussions are ongoing as to whether these differences should be reflected in regulation, or whether fluoropolymers should be subject to the same regulations as other PFAS.

Given that fluoropolymers are widely used in critical industries such as automotive, aerospace, semiconductor manufacturing, electronics, medical, chemical processing, and batteries, a total ban or severe restriction of fluoropolymers would lead to significant challenges in these sectors. The extent of the socio-economic impacts will be made available in a separate study commissioned by FPG, which will be published soon.

Fluoropolymers and their place in the polymer universe

Fluoropolymers occupy a distinctive and well-defined position within the wider polymer landscape, both structurally and functionally. While they can be considered plastics, fluoropolymers can be regarded as specialised subset. Most of the conventional polymers consist of hydrocarbon backbones linked together and surrounded largely by hydrogen. Most prominent examples are polyethylene, polypropylene or polystyrene. Fluoropolymers, by contrast, are based on monomers in which some or all of the hydrogens have been replaced by fluorine atoms.

In materials such as PTFE, the backbone is essentially a repeating $–CF_2–CF_2–$ structure. This dense fluorination has two immediate consequences. First, the carbon–fluorine bond is the strongest single bond involving carbon in organic chemistry, which makes the resulting polymer chain resistant to thermal and chemical attack. Second, the outer "skin" of fluorine around the carbon chain creates a low-energy surface that does not interact easily with other materials. Together, these features produce polymers that are inert, non-stick and stable under conditions where many other plastics would soften, swell, crack or burn. Fluoroelastomers (such as FKM and FFKM) – synthetic rubbers made by co- or terpolymerising vinylidene fluoride or TFE with other fluorinated monomers - are one of the main subcategories of the fluoropolymer family and are widely used.

Placed against the broader landscape of polymers, many fluoropolymers are part of the family of high-performance or specialty polymers. Commodity thermoplastics like polyethylene or PVC are produced in very large volumes and are designed to be cheap and versatile. Engineered plastics such as polycarbonates offer better mechanical performance and heat resistance for more demanding uses (DEK, 2025). Above these sit high-performance polymers, including polyimides, polyphenylene sulphide or polysulphones (Abbey, 2025), and the fluoropolymers. This group is characterised by the ability to tolerate high temperatures, aggressive chemicals or demanding mechanical loads for long periods.

Fluorinated polymers vs. fluoropolymers

Within the polymer universe there is sometimes confusions about "fluorinated polymers" and "fluoropolymers." Fluoropolymers are a subset of fluorinated polymers. The main difference between the two lies again in the chemical structure and more particular where the fluorine atoms are bonded within the polymer.

Fluoropolymers are polymers in which fluorine atoms are directly bonded to the carbon backbone. This characteristic carbon-fluorine (C-F) bond is the strongest and the most stable of covalent bonds as explained above, which gives fluoropolymers their unique properties.

Fluorinated polymers on the other hand is a broader term for any polymer that contains fluorine atoms in its structure. Not all such polymers exhibit the properties of fluoropolymers.

Speciality uses

In terms of function, fluoropolymers are mainly used wherever reliability under harsh conditions is critical. They line pipes and vessels in chemical plants to resist strong acids and oxidising media. They insulate wires and cables in environments where a combination of high temperature, electrical performance and fire safety is essential. They are found in seals, gaskets and membranes that must maintain performance over many years without creeping, cracking or being attacked by the process fluids.

This report focuses on fluoropolymers and does not cover the entirety of the broader group of fluorinated polymers and in particular the end-of-life (EoL) phase of such fluorinated polymers.

Fluoropolymer families, applications and end-of-life profiles

Within this high-performance class, fluoropolymers used in practice can be broadly grouped into three technical segments, which is important for understanding both their use patterns and their end-of-life (EoL) options:

1. **PTFE and modified PTFE**

This group covers PTFE homopolymer and modified PTFE grades. They are usually supplied as fine powders or moulding powders, and dispersed particles in water (so called dispersions). The moulding powders are moulded by compression and are often combined with fillers such as glass fibres, carbon or pigments. The fine powders are mainly processed by paste or ram extrusion followed by sintering. The dispersions are mainly processed by impregnation into glass fabrics or formulated to coating. Typical uses are chemically resistant linings for pipes and vessels, valve seats, seals and gaskets, membranes, filters and, to a smaller extent, non-stick cookware. These parts are usually very durable, contain fillers and are built into complex equipment such as valves, pumps or heat exchangers. Because of this, PTFE post-consumer products are rarely collected as a separate waste stream. On the other hand, pre-consumer waste handling (i.e. production scrap) and subsequent recycling is a standard procedure in many industrial settings nowadays.

Box 1-1: Illustrative case study PTFE – lined steel pipe in chemical processing plant

Use case: PTFE lined steel pipes and fittings are used in a chemical processing plant to transport highly corrosive acids and solvents. The installation includes different shapes of pipes (straight, t-fittings, etc.) as well as valves all with PTFE linings or seals.

Service life: During service life – which is expected to be longer than if conventional polymers would be used, maintenance is mostly limited to inspections and occasional replacement of individual gaskets and seals.

End-of-life: The PTFE lined pipes reach end-of-life when they are removed as part of a plant shutdown. The steel pipe bodies are still mechanically intact but replaced for safety and operational reasons. The PTFE linings and gaskets are expected to be contaminated with process residues.

Waste management options: The steel pipes are sent to a metal recycler, most commonly the PTFE linings and residual seals remain attached, they are destroyed in the metal smelting process, while the metal is recovered. Some smaller FTPE-containing components like sections with incrustations or filters, are classified as hazardous waste and are sent to hazardous waste incineration.

2. Melt-processable fluorothermoplastics

This group includes fluoropolymers that can be processed with standard thermoplastic methods such as extrusion, injection moulding and blow moulding. Typical examples are FEP, PFA, PVDF and ETFE. They are typically used for wire and cable insulation, films and laminates, corrosion-resistant linings, membranes, tubing and various components in automotive, aerospace, photovoltaic and electronic applications. In many of these products, the fluoropolymer is only a thin layer or coating on metals or other plastics, or it appears as small parts inside larger devices. These materials are usually present only in small amounts in complex waste streams such as Waste Electrical and Electronic Equipment (WEEE), end-of-life vehicles (ELVs) or construction and building products. The difficulty of separating them from other materials means that targeted recovery of these fluoropolymers from post-consumer waste is uncommon.

Box 1-2: Illustrative case study FEP- or ETFE insulated cables

Use case: FEP- or ETFE-insulated cables are used in electronic and electrical equipment operating in harsh environments (e.g. industrial control systems, semiconductor tools, or photovoltaic installations). The fluoropolymer forms a thin insulation layer around copper conductors and may also be used in cable jackets or as part of multi-layer constructions together with other plastics.

Service life: Under normal conditions, the fluoropolymer insulation does not require specific maintenance, as those cables are designed for long-term use. It is only replaced when the entire cable or device is upgraded, fails, or is decommissioned.

End-of-life: Once a cable is taken out of the installation and will/can no longer be used, it enters the end-of-life stage. Fluoropolymer-insulated cables enter usually mixed waste streams such as WEEE, ELVs or construction and demolition waste. The fluoropolymer is present only as a thin layer in complex cable assemblies and is usually not removed separately.

Waste management options: Usually the cables are shredded in specialised facilities, while the metal conductors (e.g. copper, aluminium) are recovered. The mixed plastic fraction, which includes fluoropolymer insulation together with other polymers, is typically sent to municipal waste-to-energy plants or, in some cases, hazardous waste incineration. Targeted recovery of the fluoropolymer insulation is not common due to its low concentration and the difficulty of separating it from other materials. Clean, mono-material production scrap (e.g. offcuts of fluoropolymer cable sheathing) may be collected separately and recycled by specialised companies.

3. Fluoroelastomers

Fluoroelastomers (e.g. FKM and related types) are crosslinked fluorinated rubbers used in application in which flexible seals must tolerate high temperatures and aggressive chemicals or fuels. Typical applications are O-rings, gaskets, hoses and seals in engines, drivetrains, chemical process equipment and semiconductor tools. Fluoroelastomer parts are usually small components built into larger systems, so they are generally not collected as a separate waste stream.

Box 1-3: Illustrative case study fluoroelastomer O-rings and shaft seals

Use case: Fluoroelastomer (e.g. FKM) O-rings and shaft seals are used in automotive engines and fuel systems where flexible sealing elements must withstand high temperatures, fuels, oils and other aggressive media. These seals are installed in engines, gearboxes, fuel injection systems and other critical components.

Service life: The seals are typically designed to last for most or all of the vehicle's service life and are only replaced during major repairs or overhauls. In normal operation, they require no specific maintenance beyond periodic inspection as part of standard servicing.

End-of-life: When the vehicle reaches end-of-life and is scrapped, most fluoroelastomer seals remain embedded in engines, drivetrains and fuel system components. They are usually not removed separately but enter the ELV waste treatment process together with metals and other plastics.

Waste management options: At ELV treatment plants, components containing fluoroelastomer seals are shredded together with other metal and plastic parts. Metals (e.g. steel, aluminium) are recovered, while the shredder light fraction – a mixture of plastics, rubber and other materials including fluoroelastomers – is usually sent to energy recovery (incineration) or, to a lesser extent, landfill. Maintenance waste (used seals, gaskets, hoses) is typically collected together with oily or hazardous waste streams and sent to hazardous waste incineration. Targeted recovery or recycling of fluoroelastomer seals is currently not practiced due to their small size, contamination and integration into complex components.

The focus of this project is on the following fluoropolymers, which are most frequently used by industry: PTFE, FEP, FKM, FFKM, PFA, ETFE, PVDF.

It has been confirmed by authorities that the main concerns for fluoropolymers are PFAS emissions at manufacturing and end-of-life stages. While European fluoropolymer manufacturers have initiated a "Manufacturing Programme for European Manufacturing Sites" to address emissions during production, concerns persist about PFAS emissions at the end-of-life phase. Existing literature on waste streams, waste management and recycling of fluoropolymers is fragmented and not fully up to date, this report aims to summarise it and combine it with feedback from a downstream user survey conducted within the project.

Ramboll developed in the following a comprehensive report that consolidates current knowledge and provides an assessment of fluoropolymer EoL management within the full waste hierarchy framework.

Common fluoropolymer types are summarised in Table 1-1 below, highlighting their key similarities and differences. Box 1-4 provides some helpful technical information.

Box 1-4: Explanations to Table 1-1

Please note, that the table comprises more fluoropolymers than considered in the rest of the study. Those fluoropolymers that are in the scope of the study are highlighted in blue.

Besides the name of the individual fluoropolymers, information on thermoplastic properties is provided. This is important for many different aspects like the use segment, where they end up in waste streams and which recycling routes are technically possible-

Information on the melt processability is important to consider e.g. when mechanical recycling is discussed. Such fluoropolymers can be re-melted and reprocessed.

Information on how far fluoropolymers are crosslinked in commercial practise adds another layer of information. Crosslinked fluoropolymers behave like thermoset fluoropolymers and conventional reprocessing is not possible. At EoL, this means grinding/shredding is often necessary to reduce size.

Table 1-1: Common fluoropolymer types (Fluoropolymers within the scope of this report are highlighted in blue)

Abbreviation	Full Polymer Name	Thermoplastic	Melt-Processible	Crosslinked in commercial practice	Notes
PTFE	Polytetrafluoroethylene	**Yes**	**No**	**No**	
FEP	Fluorinated Ethylene Propylene (copolymer of TFE + HFP)	**Yes**	**Yes**	**No**	
PFA	Perfluoroalkoxy Alkane (TFE + perfluoroalkyl vinyl ether copolymers)	**Yes**	**Yes**	**No**	
ETFE	Ethylene Tetrafluoroethylene	**Yes**	**Yes**	**Yes (selected grades)**	Radiation-crosslinked ETFE is widely used in wire and cable insulation. Films are typically non-crosslinked.
PVDF	Polyvinylidene Fluoride	**Yes**	**Yes**	**Yes (special grades)**	While most polyvinylidene fluoride grades remain thermoplastic, crosslinked PVDF -representing a relatively small share of total usage - is employed in high-temperature wire, tubing, and select pipe system.
ECTFE	Ethylene Chlorotrifluoroethylene	**Yes**	**Yes**	**No**	
PVF	Polyvinyl Fluoride	**Yes**	**Limited** (mostly films; difficult to melt process)	**No**	This fluoropolymer is not classified as PFAS due to its molecular structure.
THV	Terpolymer of TFE, HFP, and VDF	**Yes**	**Yes**	**Generally no**	Some niche crosslinking possible, but commercial THV is supplied as a thermoplastic. 3M (Dyneon), the sole producer of THV will end production by end of 2025.
FKM	Fluoroelastomer (mainly VDF-HFP or VDF-HFP-TFE types)	**No**	**No**	**Yes**	
FFKM	Perfluoroelastomer (fully fluorinated elastomer)	**No**	**No**	**Yes**	
FEPM	Tetrafluoroethylene–propylene elastomer	**No**	**No**	**Yes**	

2. About this report

Following the introduction chapter, the report is structured into seven subsequent chapters.

The **first chapter (chapter 3) on waste prevention** has been elaborated, as the EU Waste legislation requires the prevention of any waste as a key priority. Only if waste cannot be prevented waste management measures need to be implemented.

Subsequently**, chapter 4 is a key chapter and provides more details on the end-of-life stage of fluoropolymers** and the processes that are involved for waste management or waste recycling. Mass flows are provided to show in which waste stream fluoropolymers from different applications end up and in which subsequent waste management option the flow.

Chapter 5 – 9 are dedicated to the different waste management options, starting with the most commonly used one (hazardous waste incineration) and processing in order of decreasing use.

It should be noted, that apart from literature, information from expert interviews as well as from a questionnaire survey along the value chain (see Appendix 1 - Methodology) have been used to elaborate this report.

In the report stakeholder feedback is provided in blue boxes, while explanations and examples are provided in red boxes. Each chapter is introduced by a summary of key aspects.

3. Waste prevention

Waste prevention sits at the top of the EU waste management hierarchy and focuses on avoiding waste before it is created. Fluoropolymers are used whenever sufficient durability and resistance is required and in cases in which other polymers would fail or would require a more frequent replacement. In the following extended lifetimes are shown as collected within the value chain survey. Subsequently, a methodology is elaborated on how to calculate the reduction of waste stemming from the use of fluoropolymers.

Key messages

- Fluoropolymers are mainly used in applications that require high durability and resistance to aggressive chemical, thermal or mechanical conditions (e.g. chemical processing, transport, electronics, energy, buildings).
- In these applications, non-fluoropolymer materials would often fail much faster or may not be technically suitable.
- Stakeholder feedback indicate that fluoropolymers can extend component and system lifetimes with precise figures depending on the application and operating conditions.
- Illustrative calculations in this report show that such lifetime extensions can reduce replacement-related waste.
- In many systems, small fluoropolymer parts (e.g. gaskets, liners, coatings) protect larger components (e.g. pipes, turbochargers). This creates a “leverage effect” where a small fluoropolymer share helps avoid the early replacement of much larger parts.
- Extended maintenance and repainting intervals in construction and architectural uses also contribute to lower maintenance-related waste.
- Reuse of complete equipment (e.g. second-hand PTFE-lined machinery) is possible, which extends service life and delays waste generation.
- Data gaps exist related to material science information providing robust quantitative data and direct comparisons with alternative materials.
- The figures presented in this chapter are therefore illustrative and highlight the need for further independent, sector-specific research.

3.1 Product lifetimes

The longevity of industrial products is a key factor in resource efficiency and waste reduction. Fluoropolymers are expensive compared to traditional materials. In various industries, the use of fluoropolymers has been reported to extend the lifespan of critical components. However, the extent of this effect varies depending on the specific application, environmental conditions, and mechanical and chemical stresses involved. While fluoropolymers exhibit resistance to extreme conditions, direct comparisons with alternative materials are widely lacking in publicly available studies, making it necessary to critically assess claims regarding their durability.

Fluoropolymers are used in industrial applications where corrosion, temperature fluctuations, and mechanical wear contribute to material degradation. In the chemical process industry, petrochemical plants, and energy production facilities, fluoropolymer linings, gaskets, seals, and tubing are promoted for their corrosion resistance.

Generally, fluoropolymer products are mainly used for applications that have longer lifetimes such as application in (according to (Conversio Market & Strategy, 2023)):

- **cars** (typical age of an ELV around 12 years),
- **aircrafts** (partly exchange of fluoropolymer parts after 12 years),
- **electronic processing equipment** (usually lifetimes of 10 to 20 years),
- **chemical industrial processing** (the service life of liners and related fluoropolymer (FP) products used in chemical manufacturing typically falls between 10 and 20 years. However,

lifetimes can vary considerably: in applications involving high-purity requirements, highly aggressive chemicals, or harsh processing conditions, they may last only about a year, whereas pipes and tubes employed with less aggressive media and in milder operating environments can remain in use for up to 50 years.),

- **in pharmaceutical processing and medical applications** (average lifetimes of fluoropolymer pharma processing equipment of around 5 - 15 years; Medical fluoropolymer applications range from short life single-use products, e.g., sterile syringe filters up to several decades for PTFE covered stents) and
- **other applications;** (lifetimes of e.g.,
    - PTFE coated pots and pans on average 4 - 5 years,
    - other transport applications 15 - 25 years,
    - architectural fabrics over 25 years and
    - processing equipment in the food and beverage industry 5 - 15 years).

As examples for architectural fabrics, London's O2 arena or Munich's Allianz Arena can be mentioned. The first is built with glass cloth coated PTFE, the latter is built with ETFE, both showing that the material is in use for nearly 25 years now.

This information is in line with information provided by Wahlström et al. (2021): In highly aggressive chemical environments, such as those found in high-purity applications, fluoropolymer coatings and linings may degrade within one year. However, it needs to be noted that in such environments alternative plastics would last most likely only weeks or even only days. In less demanding environments, such as pipes and tanks transporting non-reactive substances, fluoropolymer coatings have been reported to last up to fifty years (Wahlström et al., 2021). Nevertheless, these numbers can vary depending on external factors, such as maintenance practices and operational conditions significantly impact the actual lifespan.

Also, Améduri & Hori (2023) refer to the prevention of waste, based on the durability e.g. of pumps and containers that are made of fluoropolymers and can be re-used. However, specific information regarding durability or lifetime is not provided.

Ideally, the calculation of the effectiveness of waste prevention based on the extension of lifetime increase due to the use of fluoropolymer should be calculated for the same application and be tested in direct comparison.

However, in practice it is difficult to find direct comparisons of the identical applications with and without the use of fluoropolymer. Instead, several examples of increased longevity are indicated qualitatively, as e.g. provided by Wahlström et al. (2021):

- **Electronics**: The dielectric properties of fluoropolymers have facilitated the miniaturisation of electronic components and final products, leading not only to higher durability and longevity, but also to the generation of less waste and savings in raw materials. However, a conflict in goals exists here, namely the shift in raw material consumption, towards Fluorspar, which is on the list of critical raw materials, with little or no information being provided on the recycling rates. Nevertheless, fluoropolymers have further functional advantages, as they enhance fire safety, enable high transmission speeds, and ensure the ease of installation and reliability of wires, as well as optical and data transmission cables. In some electronic applications, the use of fluoropolymers has been associated with product lifetimes lasting up to three times longer, though the exact calculations and conditions for this claim remain unverified.
- **Transport**: Fluoropolymers contribute to longer lifetimes of components and products in the automotive and aerospace industries due to their high resistance to heat, cold, fire, smoke, aggressive fluids, fuels, humidity, vibrations, and compressions. They also improve functionality by enhancing reliability, engine efficiency, weight reduction, emission control, and fuel efficiency. In automotive applications, their use has been linked to a 48% increase in fuel efficiency, measured by average fuel consumption per km over several decades. In

aerospace, they are reported to have contributed to a 93% reduction in corrosion in cargo bays and have helped prevent friction damage in helicopters. However, the precise calculations and boundary conditions for these claims remain unassessed.

- **Medical Devices and Components**: Fluoropolymers help extend the lifespan of surgical implants while reducing complications and failures caused by clogging in medical pumps and catheters. Their use in protective textiles provides a barrier against infectious agents for both medical staff and patients. Additionally, they improve the reliability and performance of medical imaging devices such as X-ray machines, MRI scanners, and CT equipment.
- **Chemical Industry**: The use of fluoropolymers significantly reduces corrosion of industrial equipment, leading to lower maintenance requirements and improved safety in chemical processing environments.
- **Building Sector**: fluoropolymer materials enhance the durability of construction components, extend their lifetimes, improve fire safety, and reduce maintenance needs over time.

In the aerospace and automotive industries, fluoropolymer-based coatings in fuel systems, hydraulic components, and insulation materials are cited as providing wear resistance and extended maintenance intervals (Henry et al., 2018). While these materials contribute to performance improvements, there is a lack of publicly available comparative data on whether they provide significantly longer lifespans than alternative high-performance materials. Similarly, in electronic and semiconductor manufacturing, fluoropolymers are used in insulation materials and protective coatings, with some sources suggesting that they can extend component lifespan by up to three times (Wahlström et al., 2021). It is important to note that all quantitative data is based on Wahlström et al., (2021), and references to the United States fluoropolymer industry report published by Wood (2020). According to the report, maintenance cost and corrosion can be significantly reduced for the US industry. In chemical and industrial processes industry maintenance costs are estimated to be in the range of USD 1.5bn (Wood, 2020). To what degree fluoropolymers reduce this cost is not stated. Instead, several other authors support the increased lifetimes on the qualitative level, indicating specific properties of fluoropolymers relevant to the specific applications, e.g. Korzeniowski et al. (2023) states that formulated trifluoroethylene-propylene copolymer (a type of fluoroethylene–propylene elastomer FEPM) components are used worldwide in many critical industrial applications where safety in harsh environments must be assured. Also, besides extending the life of critical components, the use of fluoropolymer is contributing to reducing downtime and costly repairs. This is further supported by Améduri (2023) and Améduri & Hori (2023), who discuss several examples of how the lifetimes are increased:

- **Chemical Resistance**: Fluoropolymer-lined applications such as packed towers of chemical plants withstand aggressive chemicals such as sulfuric acid, and do not lose their properties like other polymers in such harsh conditions. This resistance is due to the strong carbon-fluorine (C-F) bonds (Améduri, 2023).
- **Thermal Stability**: The Challenger space shuttle disaster in 1986 prompted the replacement of poly(thioether) seals with fluoroelastomers, which exhibit excellent heat resistance and flexibility, critical in aerospace applications. Fluoropolymers' high glass transition temperatures (Tg) and resistance to thermal decomposition ensure reliable performance in extreme temperatures (Améduri, 2023).
- **Low Permeability**: Fluoropolymer coatings on storage tanks reduce the risk of volatile chemical leaks, ensuring long-term containment in industrial and pharmaceutical facilities. This is attributed to their tightly packed molecular structures and low free volume, which minimise permeability to gases and liquids.
- **Mechanical Strength and Flexibility**: Fluoroelastomers are used in aircraft hydraulic systems (e.g., with Skydrol® fluids), offering reliable operation as they have good heat and oil resistance (Améduri, 2023).

- **UV and Weather Resistance**: Fluoropolymer-based UV and aging resistant coatings have been involved in many applications, including wires and cable, insulation, electrical applications and avionics (Améduri, 2023).

Despite the qualitative descriptions and provided reasoning how lifetime and durability is increased in the specific applications, a lack of quantitative data in relation to the prolonged use of products, components, infrastructure remains. This is also indicated by Wahlström et al., (2021), who state in their report some information on the availability of data, here shown for selected categories of measures and actions that are relevant for durability, lifetime considerations and waste prevention, see Table 3-1.

Table 3-1: Measures and actions along the product lifecycle stage and impact of fluoropolymers related to the actions in the context of circularity (based on Wahlström et al., 2021).

Measure/Action	Mining	Production	Use	End of Life
Improving product durability, reusability, upgradability, and reparability	Not relevant	No data	Yes, increased durability increases product lifespan (less waste)	No/Yes, less waste due to miniaturisation
Enabling remanufacturing and high-quality recycling	Not relevant	No data	No data	No data

Although fluoropolymers contribute to the durability of industrial and consumer products, the degree of their impact varies and is rarely quantified.

In a survey carried out in the context of the present project, fluoropolymer downstream users were asked for enhanced product lifetimes that are afforded using fluoropolymers. Based on the feedback the different applications of fluoropolymers can be summarised as follows:

Box 3-1: Summary of stakeholder feedback on lifetime extension.

Architectural and Coated Fabrics

- PVDF lacquer coatings extend the lifespan of PET/PVC membranes from 10 to 30 years.
- PTFE coatings used on glass membranes extend the lifetime to 50 years, compared to 10 years without.

Injection molding of fittings and extrusion of pipes (multipurpose) and components such as sealings/O-rings, seats for ball valves

- FP use is assumed to extend lifetime by 3-5 times
- With fluoropolymer use, the lifetime reaches 10-50 years, however there is no application that does not use FLUOROPOLYMER, as it is stated it is not possible to have these applications without FLUOROPOLYMERs

Domestic and industrial piping systems (ball valves, tribologically active seals, FKM sealing elements in industrial and fuel piping systems, PTFE filled greases, perfluorinated surfactant in chrome plating)

- 50+ years vs. 5 to 25 years depending on the application, application parameters and transported media.

Chemical Transport Systems

- In aggressive media (e.g. sulfuric acid), ECTFE-lined components last 25 years, compared to <5 years with PVC and just months with PE/PP. It is not stated in which quantities these components or systems are present or used, and what the fraction or mass of fluoropolymer is.

Dosing Pumps (Disinfection Systems)

- With conventional sealants: failure within 1 year; with fluoropolymer-based sealants: up to 10–25 years' service life.

Lubricants – Thermal Stability

- Mineral oils fail after 48 hours at 160°C.
- Fluoropolymer greases (e.g., PFPE/PTFE-based) maintain structure for 3,700 hours at 200°C and 300+ hours at 280°C.

PTFE Fry pans (Cordoba Study)

- PTFE fry pans have 2.6× longer lifetime than PTFE-free alternatives (sol-gel coatings).

Cookware and Bakeware (General Market Insight)

- PTFE-coated versions have up to double the lifetime of alternative coatings, directly reducing metal waste. The PTFE layer is very thin, and the lifetime greatly depends on the safe use by the consumer. Overheating e.g. can decrease lifetime, but safe handling guides can help to limit consumer misuse.
- If favoured properties like non-sticking is not needed the product without fluoropolymer has significantly longer lifetime.

Wind Power

- FKM sealings last 25+ years, especially critical in systems where replacement is difficult or costly.

Building Installations and Piping Systems

- Fluoropolymer-based piping systems: 20–50 years (sometimes longer).
- PVC/other plastics: 5–25 years, depending on conditions.
- In domestic infrastructure, failures lead to significant service cost, downtime, and replacement waste.

HVACR Compressors

- Lifespan: 12–26 years, up to 35 years in industrial settings.
- Fluoropolymers used in seals and insulators prevent degradation under pressure, oil, and refrigerants.
- Without fluoropolymers, lifetimes would be drastically shortened, and systems would likely fail prematurely.
- Internal failure of hermetic compressors (98% of units) leads directly to full replacement resulting in 1:1 impact on waste generation.

General Estimate in High-Performance Applications

- Respondents estimate 3–10× longer lifetimes with fluoropolymers in environments requiring high chemical, thermal, or mechanical resilience.

Employing additional sources, further examples are found that indicate how lifetime of products, components, or infrastructure is extended through the use of fluoropolymers, or how maintenance intervals are increased.

An example is reported by a paint manufacturer that employs a case example of a hotel, providing direct comparison in regard to the renewal intervals of the painting. According to the case example, the hotel was previously painted every two to four years employing polyurethane coating. When fluoropolymer-based coatings are used the painting intervals extend to 15+ years (TNEMEC, 2025). Based on that example, fluoropolymer-based coatings in architectural applications would last about four to seven times longer.

Similar increases in lifetimes are reported for architectural fabrics. Here, modern ETFE cladding systems are reported to exceed the lifetime of 30 years, while well-maintained installations can reach up to 50 years (TNEMEC, 2025). Compared to conventional glazing designs, where the most common components of the glass system that fail are the gaskets, the extended durability of ETFE cladding systems translates into extended replacement intervals and lifetime.

The above examples and especially the feedback provided by industry experts in the course of the survey demonstrate a commonly shared understanding that fluoropolymers make product and component life significantly longer in many applications. Respondents stated that these materials are critical for environments that are simply too challenging or severe for standard polymers or elastomers, as this class of materials offers outstanding chemical, thermal, and mechanical performance.

In the absence of fluoropolymers, the components of such systems would degrade much more quickly, requiring a higher degree of replacement, maintenance, and more regular production and disposal of replacement components or even entire systems. Durability itself has a significant effect in terms of decreasing the mass and the number of times that waste is generated during the lifespan of the products.

The given examples and the survey results show that typical product lifetimes of devices and equipment are multiplied significantly when employing fluoropolymers, but the actual increase strongly depends on the underlying application conditions. In some instances, it was mentioned that in the absence of fluoropolymers, the product or system would not even work, which means those materials are not only an additive that increases performance, but some could not be developed if these specific technical solutions were not possible.

Respondents also stated that if components or entire systems do not need to be replaced frequently, the associated material waste, logistical effort, energy use for remanufacturing, and emissions from transport and service are all minimised. This not only benefits environmental performance in terms

of lower material throughput, but also improves operational sustainability - for example, by reducing downtime or avoiding failure in safety-critical systems.

In addition, longer lifetime equals fewer maintenance cycles, and less cost along with less environmental burden. This is paramount in systems where getting service is costly or inconvenient, or where failure could have hazardous or life-threatening consequences on human health or safety.

But it was also evident that not all respondents were able to produce precise numbers, and they provided qualitative rather than quantitative estimates for lifetime gains, with data less available in the waste reduction categories. Several also observed the challenge in attributing the contribution of the fluoropolymer alone in complex systems possessing multiple interacting components. Some others noted that even if the benefits were evident due to experience and years of practice, but they were not quantified in a systemised manner.

Besides recycling, fluoropolymers are also kept in use by reusing complete pieces of equipment. In particular PTFE (Teflon)-lined machines are often sold on second-hand machinery websites (Exapro, 2025; Machineseeker, 2025) or through specialised dealers. In these cases, the metal equipment and the fluoropolymer lining stay together and are used by a new operator or in a new process. This extends the service life of the lining and delays it becoming waste. From a circularity perspective, this is an important but mostly undocumented pathway. Reuse of lined equipment reduces the need for new PTFE linings and avoids the early disposal of existing ones. However, these transactions usually take place outside formal waste and recycling systems, so they are not captured in statistics or material flow analyses.

3.2 Reduction of waste

The potential waste reduction benefits of fluoropolymers stem from their reported durability but quantifying these effects requires a careful comparison with alternative materials. One method for estimating waste reduction is to measure the difference in replacement cycles between fluoropolymer-enhanced and non-enhanced products.

In the year 2020 approximately 23.5 kilotons of fluoropolymer waste were collected across various industrial sectors in Europe (Conversio Market & Strategy, 2023). This indicates notable material usage and presents considerations regarding disposal methods. Fluoropolymers are predominantly used in applications with longer service lifetimes, which suggests the potential for reduced replacement frequency and waste generation (Wahlström et al., 2021).

To estimate the potential for waste reduction due to the use of fluoropolymers, the following example calculations are performed. Due to limited data availability, the examples selected are there to demonstrate the potential waste reduction effects as such. The main inputs for the calculation are:

- lifetime differences, that are taken from the results of chapter 3.1.
- mass of the component or product
- share of the fluoropolymer in the component or product

The chosen applications represent some of the main fluoropolymer sectors and their example products, representing main fluoropolymer categories (e.g. PTFE, PVDF, FKM) that account for the largest market. However, the applications themselves are chosen only to indicate the diversity of products and are not intended to be representative (Table 3-2).

Box 3-2: Guidance on how to read Table 3-2.

Columns lifetime without and with fluoropolymer

Those examples are taken from the information provided by the survey respondents. They are used as input parameters to calculate waste reduction based on lifetime-

Column mass of fluoropolymer

This value represents the mass of fluoropolymer in the product/application example in kg, e.g. the value of 0.02 in the gasket of a turbocharger means that 20 g of fluoropolymer is present in the turbocharger.

Column mass of product / component / substrate [kg]

This is the mass of the product, component or substrate that is used in the example and protected by the use of fluoropolymer, e.g. the mass of the turbocharger is 8 kg, therefore the value of 8 is present in the table. The use of fluoropolymer has in this case an influence on the lifetime of the whole product and on its total mass of 8 kg.

Column waste reduction on lifetime

Based on the input parameter in the columns lifetime without and with fluoropolymer, the waste reduction is calculated using the following formular:

$$Waste\ Reduction = \left(1 - \frac{\frac{1}{extended\ lifetime\ in\ years}}{\frac{1}{lifetime\ without\ the\ use\ of\ FP}}\right) \times 100$$

In the example gasket, the lifetime of a gasket without fluoropolymer is assumed to be 2 years, with fluoropolymer it is 8 years. To reach the lifetime of 8 years without the use of fluoropolymer, one would need 4 gaskets, with fluoropolymer it is one gasket. The direct waste reduction represents 75 % and can be also calculated via the formula, provided.

Column potential leverage (X-Factor)

The leverage factor expresses potential waste reduction due to the use of fluoropolymer considering the overall component or product. In the case of the gasket, this means that not only the gasket is considered, but also the waste reduction due to the longer lifetime of the turbocharger. The leverage effect is calculated by dividing the component or product whose lifetime is extended by the mass of a minor component that extends its lifetime using fluoropolymer. In the turbocharger example, the gasket with the mass of 20 g protects and extends the lifetime of the turbocharger with a mass of 8 kg. Dividing the mass of the turbocharger (the product protected) by the fluoropolymer component (gasket) (8 kg / 0.020 kg), results in a factor of 400. This factor needs to be multiplied with the waste reduction value of 0.75 or 75 %, which results in a leverage factor of 300. The last multiplication is necessary, as the turbocharger would have a lifetime of 2 years also without a fluoropolymer-based gasket.

Based on the examples and estimated waste reduction potential, it is shown how fluoropolymers can extend product lifetimes, even if they represent only a minor share of the total component mass. For instance, steel pipes lined with fluoropolymer exhibit service lives of up to 25 years compared to 5 years for unlined pipes, effectively reducing replacement-related waste generation by around 80% (see Table 3-2). However, considering the additional leverage in relation to mass, the waste reduction can be six-times larger than the 80% reduction due to the lifetime effect on its own. This additional leverage is present if a smaller fluoropolymer-based sub-component delays the reaching end-of-life for a larger non-FP-based component or product. This leverage effect further contributed to waste reduction and is shown separately as in Table 3-2 ("Pot. Lever"). The smaller the fluoropolymer-based component and the larger the mass of the component that relies on the fluoropolymer-component for its lifetime extension and functioning, the larger the leverage of the fluoropolymer-component that is being used. An example used in this case is a fluoropolymer-based gasket/seal of a turbo charger. The small fluoropolymer-based gasket with a mass of 20g, extends the functionality of the turbocharger that has a mass of 8 kg (in this example) from 2 years to 8 years. This effect is only present for this example, if it is assumed that the turbocharger is becoming EoL, after failing and that the gasket is not exchanged due to preventing maintenance if it had been based on non-FP-gasket.

It is important to note that this additional leverage effect is not present for components or materials that consist entirely of fluoropolymer, e.g. plastic tubes and hoses, and are compared to non-FP-based products. Here, only the lifetime extension of the fluoropolymer-component itself is present. In applications where fluoropolymers represent only a small fraction, e.g. 10% of the hose mass, such as for the example of a hose for a fuel system of a car, the incorporation of fluoropolymer not only extends lifetime of the fluoropolymer-part, but also of the rubber-based hose around the fluoropolymer-layer.

The construction and architecture applications discussed here demonstrate only the effect of extending the coating's lifetime, increasing it from 10 to 30 years. The durability of the underlying

building materials or structures remains unchanged if non-FP-coatings protect the material/substrate below the coating in a similar manner. Using fluoropolymer-based coatings allows for longer intervals between maintenance cycles for the coating, which represents a waste reduction measure. The estimated reduction of repainting-related waste is directly linked to the extension of the coating's lifetime, leading to a two-thirds decrease in waste, provided that the mass and thickness of both fluoropolymer-based and non-FP-based coatings are similar.

Reduction of maintenance-related downtime is especially important in sectors where maintenance time represents high economic losses, such as in chemical and industrial plants, where fluoropolymer-use is related to fewer maintenance interruptions and lower replacement costs and contribute to operational efficiency (Henry et al., 2018). However, these benefits are context-dependent, and industry surveys indicate that the high cost of fluoropolymers is a common discussion point (ChemService, 2021; Coherent Market Insights, 2025). Additionally, mechanical and upcycling efforts are still in development, and while upcycling technologies offer potential sustainability improvements, their large-scale implementation remains uncertain (Améduri & Hori, 2023; Schlipf & Schwalm, 2014).

The examples show waste reduction effect that is twofold: first, a lifetime extension effect, where fluoropolymer use delays replacement cycles and reduces overall waste generation; and second, in certain cases, a leverage effect, where small fluoropolymer-based parts (e.g. gaskets, liners) safeguard much larger components and thereby multiply the waste reduction achieved. However, it is to be stressed, that even though these findings demonstrate the potential effectiveness of fluoropolymers in waste reduction, they are based on illustrative calculations with limited data availability.

Table 3-2: Potential waste reduction for a selection of example applications of different sectors, based on lifetime differences, component and fluoropolymer mass (estimated values).

Sector / Application Area	FP Use	Application chosen	FP Market share[1]	Lifetime without fluoropolymer (years)	Lifetime with fluoropolymer (years)	Mass of fluoropolymer[2] (kg)	Mass of product / component / substrate[3] (kg)	Waste reduction based on lifetime[4]	Pot. Leverage[5] (x factor)
Chemical & Petrochemical Industry	Liners	Liner for steel pipes	13%	5	25	5	40	80%	6
Chemical & Petrochemical Industry	Tubes & pipes	Tube (plastic, assumption 100% fluoropolymer)	15%	5	25	5	N/A	80%	N/A
Automotive & Transport	Gasket	Gasket/Seal for a turbo charger	11%	2	8	0.02	8	75%	300
Automotive & Transport	Hose	hose for fuel system	8%	1	5	0.1	1	80%	8
Construction / Architecture	Coatings	Coatings for facades	12%	10	30	150	N/A	67%	N/A

N/A: not applicable

[1] based on Conversio (2022), applies to fluoropolymer use, not "application chosen",

[2] estimations of mass of fluoropolymer in specific application chosen,

[3] indicates the component or material mass that is protected by the fluoropolymer applied, e.g. for the first example of the steel pipe, the steel mass is assumed to be 40 kg, with 5 kg of fluoropolymer liner being applied inside to protect it, which leads to a lifetime increase from 5 to 25 years,

[4] waste reduction if the mass of the component itself is not considered, e.g. in the second example, where the tube consists of fluoropolymer as such, this is then compared to a lower lifetime of a non-FP-based tube that would last only 5 years, compared to 25 years (here fluoropolymer-use results in 80% waste reduction),

[5] fluoropolymer use considering its potential leverage, if the component to which fluoropolymer is applied is considered as well, e.g. fluoropolymer use extends the lifetime of the whole turbo charger, but from 2 to 8 years, by using only 20g of fluoropolymer gasket/seal, which has a large leverage effect on total waste generation and lifetime extension.

3.3 Value from waste reduction

The economic value associated with waste reduction through fluoropolymer use depends on factors such as material savings, waste management costs, production costs, maintenance costs and operational efficiency. Extended lifetimes may reduce waste generation by lowering replacement frequency. However, challenges related to fluoropolymer recycling remain a significant obstacle. Cost savings can be illustrated through simplified scenarios. For example, replacing a non-fluoropolymer component every five years at a cost of ten thousand euros, compared to a fluoropolymer-coated alternative with a fifteen-year service life, could result in cumulative savings of twenty thousand euros per unit over the same period. Such illustrative calculations, however, depend on actual performance in operational settings and should be interpreted cautiously until supported by independent operational data. To assess the potential economic benefits of fluoropolymer applications in terms of waste reduction, a scenario-based analysis is proposed and described in the following. This approach compares two alternative product system configurations over an identical analysis period:

- Scenario A: Product with fluoropolymer application
- Scenario B: Product without fluoropolymer application

The comparison assumes that fluoropolymer use extends the product's effective lifetime, reducing the number of replacement cycles, as well as the associated production, waste management, and replacement costs. However, the scenario provided is generic enough to be applied to different products and infrastructures. Table 3-3 provides a list of parameters that are considered in the calculation.

Table 3-3: Definition of Key Parameters for the calculation of value from waste reduction

Symbol	Component	Description
L_T	Lifetime extension	Factor by which the lifetime is extended, due to fluoropolymer use
C_P	Production Costs	Cost of producing the product per cycle
C_U	Use-Phase Operational Costs	Annual operational or running costs during the use phase
C_W	Waste Management Costs	Cost for handling, disposal, or treatment at end-of-life per cycle
C_R	Replacement Costs	Cost for administrative effort, logistics, and re-installation
T	Total Analysis Period	The total time frame considered for the analysis (e.g., 15 years)

Scenario A – with the use of fluoropolymer

The product lasts longer due to fluoropolymer durability and is assumed to cover the full analysis period with a single lifecycle. Therefore, the only costs associated with this scenario are the production costs, operational costs during the lifetime, that are multiplied with the total lifetime (here 15 years) and the waste management costs incurred at the end of the lifetime of the component or product.

The formula to calculate the total costs for the analysis period is: $C_{FP} = C_P + (C_U \times T) + C_W$

Scenario B – without the use of fluoropolymer

In this scenario, the product or component is assumed to be manufactured without the use of fluoropolymers, resulting in a shorter functional lifetime and the need for multiple replacement cycles over the total analysis period (e.g., 15 years). Due to the limited durability of non-FP materials, the product must be replaced at regular intervals. Each cycle includes a new production phase, an operational phase, and a waste management event. Additionally, every replacement involves replacement-related costs such as administrative efforts, logistics, and potential downtime. If it is

necessary to shutting down a plant cool down times and heat up periods are required. The lifetime extension factor L_T is defined as the ratio between the service life of the FP-based component (assumed to cover the full analysis period T) and the service life of the non-FP alternative. Consequently, the non-FP product has a lifetime of T/LT, resulting in LT full lifecycles over the analysis period.

Therefore, the calculation of costs for this scenario can be done according to the following formula: $C_{noFP} = L_T \times (C_P + C_W) + (L_T - 1) \times C_R + (C_U \times T)$

Given the limited availability of empirical data, the need for several assumptions in the calculations, and the strong variability across applications, scales of use, and operational contexts, it is not possible to derive a robust quantitative estimate of the overall value from waste reduction. However, this represents a potential research direction, that could be performed by academia around the fields of industrial ecology or waste and resource management, such as provided by Kleemann et al. (2017), Lederer et al. (2019) or Miatto et al. (2019), for the building stock, also partially including industrial buildings or infrastructure. However, separate studies are required for different sectors to estimate the stock and the flows of fluoropolymer-based applications. The examples provided should therefore be regarded as indicative illustrations of potential effects rather than representative market-wide figures. Further empirical data and sector-specific studies would be required to substantiate and generalise these findings.

4. Fluoropolymers at its EoL stage

In this report, **end of life (EoL)** describes the stage when a product, component or piece of equipment can no longer be used for its intended purpose and is removed from service. At end of life, it becomes waste and must be managed in some way. How and when end of life is reached and which treatment option is chosen can influence factors such as resource use, costs and potential environmental impacts of a product.

The following chapter first provides an overview on the quantities of fluoropolymers at EoL stage and subsequently shows and discusses the main waste streams that exists today. Finally, a general chapter on management of the different waste streams is provided.

Key messages

- Based on the available data, it can be estimated that fluoropolymer production and use in the EU are in the range of 40,000–52,000 t per year (polymers in primary form) (Wahlström et al., 2021; Wood, 2022).
- In 2020, around 23,500 t of fluoropolymer-containing waste was collected. Fluoropolymers represent <0.01% of total EU waste by mass, compared with about 4.8% for plastics overall (Conversio Market & Strategy, 2023).
- A large share of fluoropolymers is expected to be present in imported and exported articles (e.g. transport, electronics), but these flows are not captured adequately in official statistics, so the overall fluoropolymer balance in products and waste streams remains only partially quantified.
- The main fluoropolymer waste streams identified for 2020 are commercial and industrial waste (around two-thirds of fluoropolymer waste), waste electrical and electronic equipment (WEEE) and end of life vehicles (ELVs) (Conversio Market & Strategy, 2023). In practice, WEEE and ELV fractions seem to be often treated jointly in metal shredding plants.
- In the EU, hazardous waste incineration is currently the dominant end-of-life option for fluoropolymers, complemented by municipal waste-to-energy combustion, landfilling, and thermal destruction during metal recycling. Recycling represents only a small share of total fluoropolymer waste treatment and is focused mainly on clean production scrap (Conversio Market & Strategy, 2023).
- A distinction is needed between production waste and post-use waste. Clean, relatively pure production residues are often recycled or reused, whereas post-consumer fluoropolymer waste in complex assemblies is generally incinerated (hazardous waste incineration) or landfilled due to small quantities and separation challenges.
- Stakeholders report multiple barriers to wider fluoropolymer recycling, including legal uncertainty (e.g. future PFAS restrictions, REACH compliance, end-of-waste status), limited infrastructure and incentives, contamination in some applications, technical separation limits, and lack of established markets for secondary fluoropolymer materials.
- Some upcycling approaches face technical barriers that still limits the commercial use of these processes.
- Most fluoropolymer-containing products are currently designed for performance and longevity rather than for recyclability or end-of-life management.

4.1 Quantities of fluoropolymers at its EoL stage

Data on overall volumes of fluoropolymers produced and used in the EU are available from several sources Wood, 2022; Dalmijn et al., 2024). However, these sources show notable variability, leaving room for interpretation, and reported figures have also changed over recent years. This includes structural changes in the industry, as some manufacturers have withdrawn from fluoropolymer and broader PFAS production. For example, 3M has announced a complete exit from PFAS manufacturing,

including fluoropolymers, by the end of 2025. Therefore, for an overview of the EU fluoropolymer market, reference is made to a study commissioned by FPG, which is planned for publication in 2026.

On the EoL side, a total of 23,500 t of fluoropolymer-containing waste was collected in the EU in 2020 (Conversio Market & Strategy, 2023). These include applications from various sectors such as waste from

- automotive industry,
- aerospace,
- electronics & semiconductors,
- chemicals,
- medical and pharma as well as
- others such as professional cookware.

Fluoropolymers are expected to represent less than 0.01% of the total waste collected in the EU, compared to 4.8% for plastics overall.

However, there are statistical gaps between the total of generated waste and officially collected quantities. For example, according to the Heinrich-Böll Foundation, in 2021 only half of the ELVs are officially recorded by statistics as only 50% of the ELVs are handled in authorised recycling facilities (Conversio Market & Strategy, 2023).

4.2 Main waste streams today

The main waste streams for fluoropolymers in the EU in 2020 include:

- Commercial and industrial waste from various streams: The largest share, 15.1 kt, comes from chemical processes, energy production, food and beverage industries, pharmaceuticals, and semiconductor manufacturing. These applications use fluoropolymers for pipes, seals, membranes, and other durable components.
- ELV (End-of-Life Vehicles): Approximately 3.0 kt comes from end-of-life vehicles, with fluoropolymer content per vehicle estimated at 0.35–0.4 kg (Conversio Market & Strategy, 2023).
- WEEE (Waste from Electrical and Electronic Equipment): 2.3 kt of fluoropolymer waste was collected in 2020 from electronic waste, including semiconductor manufacturing equipment.

The flow-chart below is prepared based on data provided in the Conversio study. It shows the waste collected in kt for the most relevant sectors (left) connected to different waste streams (middle) as well as waste treatment (right). The illustration integrates information from several tables contained in the Conversio study. One of the tables (see slide 41 of the study) provides information on the treatment of fluoropolymer waste quantities per industrial sector, and the other table (see slide 42 of the study) on the treatment of waste quantities per waste stream. The link between collected fluoropolymer-containing waste from the different sectors (left) and waste streams (middle) was estimated based on a graph from the Conversio study (see slide 38 of the study), which illustrates the waste quantities per sector in connection with the waste streams.

The Conversio study does not distinguish between hazardous waste incineration and municipal waste-to-energy combustion, while this is an important information related to the end-of-life treatment of fluoropolymers.

In the figure below, it is considered that besides residential household waste also fluoropolymer in electronic waste (WEEE) and in ELV including auto-shredder residue (ASR) ends up in municipal waste-to-energy combustion. This is due to missing precise data in this regard and indications of WEEE

(Cardamone et al., 2021) and ASR (Conversio Market & Strategy, 2023) ending up in municipal waste-to-energy combustion.

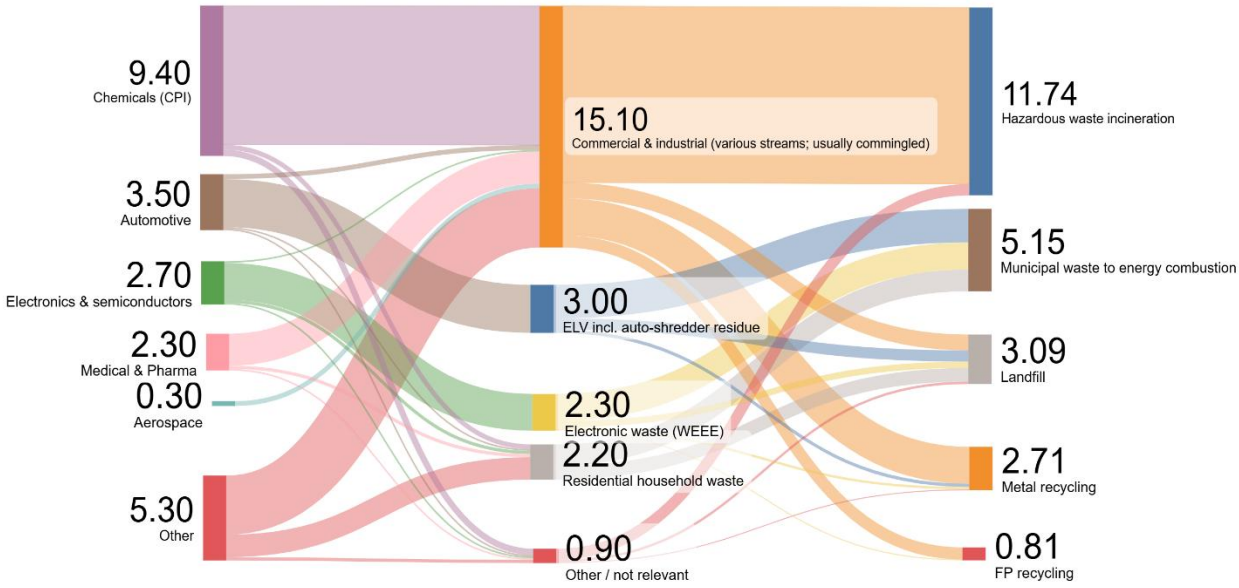


Figure 4-1: Mass flows from fluoropolymer waste generation by sector (left), waste streams (middle) and final waste treatment (right), 2020, all data in kt, own illustration based on Conversio (2022)

In the transport sector, products that incorporate fluoropolymers are generally designed for extended use, whereas in the electronics field, their service lives differ depending on the specific device or application. Waste originating from both sources (ELVs and WEEE) should be treated as separate waste streams with specific pre-treatment technologies as both waste streams are governed by two different legislations. WEEE is governed by the EU WEEE Directive and must be collected separately because it contains both valuable metals and hazardous substances (e.g. mercury, flame retardants). Waste Vehicles including their collection and treatment are regulated via the End-of-Life Vehicles (ELV) Directive. The need to recover remaining metals and energy from this fraction is often stressed. For WEEE recycling, specific routes are described including manual dismantling, shredding and mechanical and/or hydrometallurgical separation for metals (copper, precious metals, etc.) (L. Zhang & Xu, 2016), while for ELVs, specialised ASR metal-recovery technologies (e.g. FinesTuning®) are available. However, while the pre-treatment lines are mostly separated, it seems that the metal fractions they generate can converge. Waste arising from the automotive and electronic sectors typically end up in metal shredding plants and are often treated jointly (Wahlström et al., 2021). Also, the Industrial Emissions Directive (Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on Industrial Emissions (Integrated Pollution Prevention and Control), n.d.) does not distinguish and uses the category "treatment in shredders of metal waste, including waste electrical and electronic equipment and end-of-life vehicles and their components". Several sources indicate incorrect handling of WEEE as generic metal scrap (Baldé et al., 2020; WeeeForum, 2022) and policy discussions are ongoing. EuRIC, which is the European Recycling Industies' Confederation raises in a position paper from 2024 concerns concerning "introducing a complete ban on mixing ELV with …] waste electrical and electronic equipment (WEEE)" (EuRIC, 2024). According to them, today, shredder output quality is largely driven by customer specifications. Pre-sorting materials into separate streams before shredding does not automatically guarantee a better environmental performance. In fact, jointly processing ELVs and WEEE can increase the overall efficiency of the recycling process and prolong the service life of the

equipment (for example, the shredder hammers). This underlines the assumption that ELV and WEEE are commonly processed together.

Before the shredding stage, certain recyclable plastic parts - such as car bumpers, fuel tanks, and selected plastic components from electronic devices - are separated for reuse or recycling. Metals that are coated or combined with tightly bound materials are directed to high-temperature smelting operations to enable metal recovery. A standard passenger vehicle is estimated to contain approximately 350 grams of fluoropolymers (Ameduri, 2018) probably based on bottom-up assessments of typical automotive applications such as fuel systems, seals, gaskets, wiring, and sensor components. This translates to roughly 4,200 tonnes of fluoropolymers entering the waste stream from end-of-life vehicles in Europe annually, based on the deregistration and disposal of about 12 million cars each year. For the future market data suggest that the fluoropolymer content per vehicle may increase, driven in particular by electrification (e.g. lithium-ion batteries, fuel cells, high-voltage wiring and thermal management systems. Therefore, the quantity of fluoropolymers used per vehicle is expected to rise, although precise quantitative data are rare like the estimate of Améduri (2020), who projects FP content in vehicles to increase to between 1 and 2 kilograms.

During vehicle shredding, most of the plastic materials - apart from components such as bumpers, fuel tanks, and batteries - are directed into the shredder's light fraction. This stream is made up of a mixture of plastics, rubber, wood, and other non-metallic residues, with plastics typically accounting for about 20–40% of the total (Zevenhoven & Saeed, 2003). Wahlström et al., (2021) indicate – based on statistical data from 20 European countries accessed in 2020, that about 0.86 million tonnes of shredder waste were treated in 2017 of which 34% was landfilled, 33% incinerated with energy recovery and 33% recycled. However, it is unclear which portion of the 33% incinerated for energy recovery are incinerated in a hazardous waste incineration plant and how much goes to municipal waste-to-energy-recovery.

At a global level, a specific share of WEEE, namely photovoltaic (PV) waste from PV installations, is rapidly increasing. From 45,000 tonnes in 2016 it is estimated to reach 60 million tonnes by 2050. According to a 2025 report from the JRC, the EU generated 123,910 tonnes of PV waste in 2023. Projections for 2050 range from 16 million tonnes to 23.5 million tonnes (European Commission. Joint Research Centre, 2025).

4.3 Management of fluoropolymers at EoL

Wahlström et al. (2021) indicate based on (Dams & Hintzer, 2016; Geyer et al., 2017; Hintzer & Schwertfeger, 2014) that 60% of fluoropolymers in products are currently landfilled, and 12% are incinerated across the world. Of the remaining 28% only a minor part is recycled. Percentages in the EU differ, however, significantly from those figures with incineration being the main waste management option. In the EU, landfilling rates have been reduced through policy measures, and mixed or composite fluoropolymer-containing components are often difficult to separate at end of life. As a result, such wastes are frequently directed to controlled incineration routes rather than landfilling, not because fluoropolymers are intrinsically hazardous, but because they are embedded in complex articles or contaminated streams for which regulatory-compliant recycling or disposal options are limited. Fluoropolymer waste is therefore managed through various treatment routes depending on product design and end-of-life conditions. (Conversio Market & Strategy, 2023):

- Hazardous waste incineration: 50% of collected fluoropolymer waste (around 11.7 kt) is incinerated in hazardous waste incineration plants.
- Municipal waste-to energy incineration: 22% of the collected waste (around 5.2 kt) is expected to be incinerated in a municipal waste-to-energy incineration plant. This percentage assumes that WEEE and ASR waste streams are directed to municipal waste to energy recovery

- Landfilling: About 13% (around 3.1 kt) of fluoropolymer waste is disposed of in landfills, typically for chemically inert or non-recyclable materials.
- Metal recycling: About 11.5% (around 2.7 kt) of collected fluoropolymer waste are thermally destroyed during metal recycling
- Recycling: About 3.4% (around 0.81 kt) of waste is recycled, including mechanical recycling (e.g., conversion to micro powders) and upcycling approaches.

Results from the value chain survey conducted within the present project confirms that hazardous waste incineration is currently the most common waste management practise for fluoropolymers in the EU.

Box 4-1: Summary of stakeholder feedback - End of life of different products and their waste management

In the case of industrial lubricants, greases, and oils comprising fluoropolymers, incineration is the primary technique for disposal. In practice, these materials are generally disposed of following EU best available techniques (BAT) (hazardous waste incineration at > 1100°C) because recycling is rarely feasible due to contamination and the difficulty of separating them from mixed waste streams or associated equipment.

Items such as **seals, gaskets, valve seats, and coated hardware** (used in infrastructure, buildings, and industrial applications, respectively) are similarly mostly sent to hazardous waste incineration at end of life. Many of these components are integrated into long-lived systems (such as underground =pipes or fixed installations), and are therefore not separately removed, but instead lift in place or scrapped together with larger assemblies. In cases where fittings or valves consist of mixed metal and plastic materials, metal fractions may be recovered during dismantling or shredding. However, the fluoropolymer fractions are typically destroyed either during high-temperature metal processing or during hazardous waste incineration. At present, no systematic recovery route exists for these fluoropolymer components.

Plastics based on fluoropolymers contained in **electronic components and WEEE** (waste electric and electronic equipment) are treated in accordance with the WEEE Directive or the national legislations. The products are often shredded, and metals are recycled. Fluoropolymer components either wind up in the residue plastic fractions or are destroyed by thermal treatment. Fluoropolymer containing plastic separated upstream of metal recovery are generally assumed to be directed to either hazardous waste incinerators or municipal waste-to-energy plants. The fate of fluoropolymers within micro-parts (e.g., coatings or insulators remains less well documented.

Medical and laboratory items with fluoropolymers are almost always classified as hazardous or medical waste and are incinerated in hazardous waste incinerators. These waste streams are often contaminated with body fluids, pharmaceuticals or similar substances. Typical examples include disposable medical products, lab tubing, filters, or pharmaceutical packaging. Such items are usually discarded according to controlling GMP or some related specifications and assigned to specific categories of medical hazardous waste Responses to this question indicated that recycling is not possible for these products because they are contaminated with the active substance or biomaterial.

Fluoropolymer-coated cookware and other goods (such as PTFE applied to non-stick pans) are typically disposed of by way of metal recycling when possible. Metal parts are removed from household waste and sent to metal recycling plants in countries with dedicated collection systems, where fluoropolymer coatings are destroyed during high-temperature metal processing. Where such systems do not exist, however, cookware could still make its way into municipal solid waste destined for eventual municipal waste-to-energy incineration or landfill.

Automotive and transport-related parts such as fluoropolymer-based gaskets, bushes, grease, and cables would usually be disposed of by end-of-life vehicle (ELV) scrapping. Shredding and density separation are used to recover precious metals (copper, steel, and aluminium). Most often fluoropolymer components are not manually dismantled, since it is not economically viable for such a small amount of material. Cables are shredded for metal reclamation, and insulation and coatings containing fluoropolymers are thermally destroyed in some cases.

In **building and infrastructure applications**, such as long-life specialist industrial filters or bearings (bridge to allow expansion / contraction), fluoropolymers are either incinerated or landfilled. Some **products remain in place** for decades and are rarely retrieved. Components that are removed, such as filters, are incinerated in hazardous waste incinerators.

Fluoropolymers are increasingly used in **architecture** as lightweight, durable foils for facades and roofs, particularly in the form of ETFE and, to a lesser extent, FEP films. ETFE and FEP foils combine high transparency, UV and weather resistance, chemical inertness and low surface energy, which makes them self-cleaning and suitable for long-lived membrane constructions. A flagship example is the Allianz Arena in Munich, whose facade and roof are formed by thousands of inflated ETFE-foil "cushions".

For **textiles and technical fabrics used by consumers** with fluoropolymer finishes or membranes, the most mentioned options are incineration and landfilling, depending on the regulations in the local area and whether the textiles may be considered hazardous because of additives. For incineration, both options – hazardous waste and municipal waste-to-energy incineration is therefore a possible end of life pathway. Recycling is seldom conducted even if textiles include recoverable polymers, due to separation cost.

Several responses referred to **clean production waste** (e.g., PTFE trims or "coating failures"). These are often separately collected and recycled or reused. Where disposal by a third-party waste handler is required, such materials are generally not sent to hazardous waste incinerators, except in specific cases where hazardous additives are present. Instead, the more common disposal route for solid, uncontaminated fluoropolymer processing scrap is co-incinerated with other commercial waste, mainly in municipal waste-to-energy plants. It should be noted that this disposal pattern applies only to pre-consumer production waste. Post-use waste streams typically follow different treatment routes and are not covered by this description.

Some of the **high-performance industrial machinery manufacturers** indicated that recyclers dismantle their EoL machines. One respondent indicate that their machines are made primarily of recyclable metals. These machines have fluoropolymer (FP) parts as attachments that are burnt out during the metal melting process at > 1300 °C. The same respondent indicated that certain small PFAS containing parts, such as O-rings, that are replaced during a service, are typically nowadays gathered […] and burnt at temperatures of a municipal waste-to-energy incineration plant (> 850°C for 2 seconds). It is discussed in the response, that at these temperatures, PFAS could still be present in rest fractions, but the PFAS weight in these O-rings is marginal versus the total PFAS weight in machines and spare parts. However, incineration in hazardous waste incinerators(>1.100°C) is considered for the future.

In business-to-business distribution models, suppliers often lack visibility into end-of-life management due to limited contact with end users and the independent responsibility of intermediaries and end users. In the absence of product-specific disposal data, standard regional waste management pathways are commonly assumed for analytical purposes.

Differences exist between production waste and post-use waste. Between roughly one-fifth and one-quarter of fluoropolymer producers reportedly recover production waste losses through in-house recycling. About 30–35% send their waste to specialised recyclers, while around 15% ship it to other companies within the EU and a further 5–10% export it outside the EU, mainly to Asia. The remaining ~15% of fluoropolymer processing losses are not recycled at all but are disposed of via hazardous-waste incineration (Conversio Market & Strategy, 2023). Production waste is often clean and can be used effectively for recycling / re-use. Various options are described in the following chapters and are also indicated in (OECD, 2025). Only a few respondents indicated that production scrap is collected and sent to a third-party provider for processing via incineration. It is expected that this is mostly true for solid fluoropolymer processing scrap that is finally co-incinerated with other commercial waste, mainly in municipal waste-to-energy plants. Only where the material is classified as hazardous (e.g. due to specific additives or contamination) is it routed to dedicated hazardous-waste incinerators.

Unlike many conventional plastics, fluoropolymers retain a relatively high economic value at end-of-life, which should make recycling attractive in principle (Ebnesajjad & Khaladkar, 2005) as cited in (Wahlström et al., 2021)). Stakeholder feedback emphasised, however, that in practice, recovery efforts are largely limited to clean production residues rather than post-consumer material echoing findings from Wahlström et al. (2021).

As reasons stakeholders indicated the following:

Box 4-2: Stakeholder feedback – barriers to recycling

- **Legal uncertainty:** Recycled materials may not meet REACH compliance, especially under future PFAS bans, which could prevent fluoropolymer-containing recyclates from gaining "end-of-waste" status. Furthermore, the PFAS regulations are expected to create new challenges for collection, traceability, and regulatory acceptance of recycled fluoropolymer content. Also, regulatory developments such as the ELV Directive revision create uncertainties about the role of fluoropolymers in future frameworks.
- **Limitations of circularity within a use:** In several regulated applications, the use of recycled materials is restricted or not allowed. As an example, drinking water regulations in many countries do not permit recycled plastics in contact with potable water, which limits reuse of fluoropolymer-based pipes, fittings, and seals in water systems. Other constraints exist in medical, food-contact and aerospace applications where strict safety and performance standards and approval and certification processes are usually based on virgin materials. Using recyclates in these sectors would require extensive re-testing and re-approval and is in some cases not allowed at all, which significantly limits within-use circularity for fluoropolymers.
- **Lack of infrastructure and separation challenges:**
  Infrastructure, collection systems, and economic incentives to support fluoropolymer recycling or proper waste handling are largely absent. Where fluoropolymers are present only in small quantities or are difficult to separate from other materials, recovery efforts are uneconomical with current separation technologies. In practice, there is very limited dedicated infrastructure or collection systems for waste containing fluoropolymers, and beyond the requirement to comply with existing waste-disposal legislation, few positive economic incentives exist for separate collection or higher-value recovery.
- **Contamination:** Many fluoropolymer applications in medical, pharmaceutical, and filtration sectors are exposed to hazardous substances that could make recycling unsafe or technically unfeasible. For example, HEPA filters accumulate a wide variety of contaminants that cannot be removed effectively, preventing their recycling. These materials are therefore typically incinerated as hazardous waste or mechanically shredded or ground in enclosed systems. The resulting dust is captured in enclosed extraction and filtration systems, collected as hazardous waste, and then typically sent for hazardous waste incineration or, where appropriate, stabilised and disposed of in hazardous waste landfills.
- **Economics and secondary raw materials:** Recycling processes are costly and often less economical than producing virgin material. In many cases, it is more cost-effective to use virgin material instead of recycling production scrap especially when recycled fluoropolymers may not meet the required material properties for high-performance applications. Where fluoropolymers are only present in small quantities or are difficult to separate from other materials, the effort and expense to recover them are not justified by their market value. Furthermore, there is no established market or reliable value chain for secondary fluoropolymer materials. As a result, there is little economic incentive for recyclers or manufacturers to invest in recovery systems.
- **Long service lives delay waste appearance:** Because many fluoropolymer applications are long-lived (often several years or decades), only a small fraction of the material placed on the market in a given year appears as waste in the same period, which slows down the build-up of recyclable volumes compared with short-lived plastics such as packaging.
  Current design priorities vs. recyclability: Survey results indicate that designing fluoropolymer-containing articles with end-of-life in mind is not yet common practice: around 30% of respondents answered “yes”, about 60% “no” and roughly 10% were undecided or qualified their response. Many respondents also emphasised that current designs prioritise high performance, durability, and safety, which can conflict with design-for-recycling considerations.

All available data confirm that nowadays incineration is the main disposal route of fluoropolymers, even though the EU Waste Hierarchy defines a clear hierarchical order in the management of waste for the prevention of pollution and the promotion of the circular economy. Prevention is at the top of the scale and involves preventing waste from being created at all, e.g., eco-design, resource-efficient use, and product longevity. The use of fluoropolymer contributes to extended product lifetimes (see chapter 3), however, robust quantitative data to accurately quantify this effect are currently limited. If waste cannot be eliminated, then the best course of action is to make items ready for re-use and recycling, where

materials are converted into new products. If not recyclable, energy recovery may be utilized for treating the waste. Disposal should be considered only if no other feasible alternative is available.

In the manufacturing processes for PTFE, operations such as moulding, sintering, machining and cutting typically generate between 10% and 30% of the input material as scrap, with some processing steps producing over 50% (Wahlström et al., 2021), emphasising that a significant amount of material may be available for recycling. However, this example is not representative for all fluoropolymers as it is known that PTFE processing is particularly inefficient due to its poor melt processability, which necessitate multi-step forming and extensive post-machining. Other fluoropolymers, such as FEP, ETFE & PFA, have improved manufacturing efficiency , so that only limited scrap material is produced.

The focus on recyclable material especially at the PTFE production stage explains why recycling activities are currently focused upstream. At the same time, it highlights a structural challenge - once fluoropolymer-containing products reach the market, they are typically used in long-life applications, often in complex assemblies, which makes later recovery both technically and economically difficult.

In the following box, feedback from the value chain survey is provided to provide a more detailed insight into the current situation.

Box 4-3: stakeholder feedback regarding recycling efforts

Several respondents indicated that they are **engaging in collaborative initiatives to improve the waste processes for fluoropolymers**. Some companies participate in research projects, task forces, or are in contact with raw material suppliers to explore treatment options and long-term solutions for fluoropolymer waste. A few mentioned involvements in pilot programs, such as those developed with architects aiming for more sustainable building designs that take end-of-life issues into account. These projects are often still in early phases and are expected to be long-term in nature. Other respondents pointed to technical collaboration with waste contractors or recycling companies. In some cases, companies are working directly with service providers to ensure proper sorting and destruction of fluorinated waste, even in the absence of specific regulatory requirements. This includes setting up internal recovery processes to reprocess end-of-life material into semi-finished products, which are then used in the manufacture of new components. There were also examples of companies exploring the recycling of specific compound streams, indicating interest in developing tailored approaches for more complex material types. A few responses reflected participation in upcycling projects or material trials. While outcomes of these efforts are not always publicly available, they point to growing interest in circular approaches.

When being asked if there are **noticeable trends in the disposal methods** a few companies noted that customers are beginning to place more value on recycling and circular economy models. For instance, one respondent explained that their organisation has launched initiatives to explore circular business models. These include reaching out to customers, gathering data, and collaborating with partners to recollect end-of-life articles, regranulate them, and reintroduce the materials into the same value chain. Other respondents and in particular experts being interviewed spoke about setting up circularity / closed-loop systems in a broader context. Major waste streams in which fluoropolymer material is appropriate for recycling (sufficiently high volume, relatively pure and uncontaminated) are used to feed EoL material into the recycling processes and appropriate uses for the secondary raw material are in place in which the potentially changed properties of the fluoropolymer do not pose any difficulties.

Some noted that **product design and lack of transparency** (e.g. in product composition) present additional obstacles. The absence of documentation, such as a digital product passport (DPP), was cited as a key gap. Also, certification and safety regulations were mentioned, especially in sectors like food contact or electronics, where use of recycled material would require requalification or is outright restricted. The design phase of packaging is also being influenced by EU regulation. One respondent mentioned that packaging is increasingly being created with design for recycling in mind, in compliance with the EU Packaging and Packaging Waste Regulation (PPWR).

The evaluation of responses to the survey question on whether articles containing fluoropolymers are designed with considerations for recycling or sustainability shows that recyclability is generally not a primary design objective at present. This outcome reflects the context of many fluoropolymer applications rather than a general absence of end-of-life considerations. In several uses, including regulated sectors such as medical devices, design choices are primarily driven by performance, safety, and regulatory compliance, and the use of recycled materials may be restricted or not permitted at all due to hygiene, sterility, or traceability requirements. Among the

respondents, approximately 30% indicated that recycling considerations are taken into account, while around 60% reported that this is not the case, and the remaining ~10% were undecided or provided qualified answers. These responses are consistent with the understanding that designing for recycling and designing for end-of-life are not the same. End-of-life considerations may focus on durability, safe use over long service lives, controlled disposal routes, or compliance with hazardous-waste legislation, particularly in sensitive applications. By contrast, designing specifically for material recycling is a more narrowly defined objective and is not feasible or appropriate in all regulated uses, including parts of the medical, pharmaceutical, and food-contact sectors, where regulatory frameworks explicitly allow exemptions from recyclability requirements to protect health and safety.

Among the 'Yes' answers certain products are inherently designed for recycling, particularly when pure fluoropolymers are employed (e.g., as in some piping and coatings). Some mentioned that they have implemented a design strategy that aims to make **material separation feasible**, suggesting an intention to support potential **recycling schemes**.

But most people stated 'No', noting that designs focus more on creating a high-performance, durable, and safe product rather than something that can be recycled. Technical constraints in many sectors restrict the feasibility of recyclable-friendly design. It is frequently not possible, or not economical, to separate fluoropolymers from compounded or complex systems, such as coatings, gaskets, or composites. This is particularly applicable in medical, chemical, or high-performance industrial applications where components are required to perform rigorously for long periods, which can be at the expense of end-of-life considerations.

The concept of end-of-life design for articles containing fluoropolymers is increasing in importance, though not universally applied. Current design strategies strongly support the technical function and longevity of products, while recycling strategies are in their initial stages or non-existent. Future advances could be driven by regulatory drivers, sector-specific guidance, and technology developments that enable recycling or reuse of fluoropolymer parts to become a more practical and cost-effective proposition.

Often the term upcycling is used when it comes to fluoropolymers recycling or reuse. Upcycling is described as a thermo-chemical recycling, which splits the polymer back into the corresponding monomers, which, when cleaned, can be re-used for polymerisation of neat fluoroplastics (pro-K, 2018). While such approaches are conceptually attractive, there are also barriers to full scale implementation.

In principle, fluorinated polymers can be "upcycled" by recovering fluorinated monomers such as tetrafluoroethylene (TFE) or related intermediates, which can be reused as feedstock. Pilot projects and concepts developed by industry and technology providers indicate that such approaches are technically feasible in controlled settings. However, several factors currently limit their applicability at larger scale:

- **High purity requirements:** Regenerated monomers must be very pure in order to be suitable for fluoropolymer production. TFE, in particular, is very sensitive to impurities. Even small amounts of hydrogen-containing species can disturb polymerisation. While lower-purity streams may be usable for certain applications such as telomerisation, they are generally incompatible with the production of high-performance fluoropolymers, including PVDF.
- **Hazardous properties of TFE:** TFE is reactive, can decompose explosively, and is classified as a carcinogen (Carc. 1B) according to Regulation (EG) no. 1272/2008. As a result, its production, purification, storage and handling require strict safety measures. Transport is especially difficult due to its explosive behaviour, making co-location of monomer generation and polymerisation sites preferable. Storing TFE, especially in liquefied form, is energy-intensive and increases operating costs.
- **Limited scope of current pilots:** Existing pilot projects mainly address clean, well-defined fluoropolymer residues and are not yet widely applied to mixed or post-consumer PVDF waste More generally, it should be noted that upcycling pathways producing TFE reintroduce many of the same technical, safety, and purity constraints associated with conventional fluoropolymer production. Where TFE cannot be generated directly via upcycling, it depends on CaF_2, a critical raw material without any natural sources in Europe.

In chapter 9, more details on recycling are provided showing that processes and the technical know-how exist in Europe for specific processes, but that still technical barriers exist that limit the possibilities. On the other hand, a growing demand from Asian countries for secondary raw material and upcycling technologies is currently being experienced.

5. Hazardous waste incineration

As described in section 4.2, industrial applications account for the largest share of fluoropolymer use in Europe. Accordingly, Figure 4-1 shows that 50% of the annual end-of-life fluoropolymer mass in 2020 (11.74 kt) flowed to hazardous waste incineration. The following chapter summarises information on the fate of fluoropolymers in European hazardous waste incinerators.

Key messages

- Fluoropolymers are widely used in industrial applications that result in end-of-life fluoropolymers being managed via hazardous waste incineration.
- A conservative estimate for the average concentration of fluoropolymer in European hazardous waste is calculated to be 1.12 kg fluoropolymer/t hazardous waste (~0.1%).
- In accordance with European regulations for hazardous waste incineration, rotary kiln incinerators operate above minimum standards and typically maintain secondary combustion chamber temperatures between 1050°C and 1300°C for a gas residence time of 2 seconds.
- Rotary kiln incinerators are approved by the United Nations Environment Programme for environmentally sound destruction of solid, liquid, and gaseous fluorocarbon materials.
- Based on incineration chemistry, it is predictable that (a) hydrogen fluoride (HF) is the dominant fluorinated product from combustion of the gases evolved from fluoropolymer pyrolysis and (b) this HF reports to calcium fluoride (CaF_2) or sodium fluoride (NaF) in the solid residue from flue gas treatment.
- Full-scale hazardous waste incinerator testing shows that air emissions of water-soluble PFAS emissions are extremely low, so low that measured values are influenced by background PFAS contamination from scrubber supply water or on sampling/analysis equipment.
- A conservatively estimated emission factor is computed as less than 1 g water-soluble PFAS/tonne fluoropolymer incinerated (0.0001%) ignoring the effect of other organofluorine material input to hazardous waste incineration and external contamination observed during stack testing. This is comparable to a destruction efficiency of greater than **99.9999**%.
- Since most of the separately measured volatile fluorinated compounds are recognised greenhouse gases, the effect of their emissions can be assessed via comparison to CO_2 emissions. Assuming presence at the detection limit for non-detect values, the Climate Impact of three of the most potent greenhouse gases (CF_4 + $C2F_6$ + CHF_3) are shown to be thousands of times less than the incinerator's CO_2 emission concentration.

Fluoropolymers used in industrial applications (e.g., gaskets, seals, tubing) are typically contaminated with process materials when removed from service at end of life (Drobny & Ebnesajjad, 2023). Consequently, these end-of-life polymers are placed in containers (e.g., 200 litre drums) where they are commingled with other solid waste (e.g., concurrently generated during the same maintenance activity) and sent to hazardous waste incinerators. These hazardous waste incinerators are designed to assure destruction of the contaminants and other organic materials in the waste and operated in accordance with the BAT (Best Available Techniques) Reference Document (Neuwahl et al., 2019) to control emissions to the environment. Europe has over 90 hazardous waste incineration plants (Schmidt, 2026).

5.1 Relevant Regulations

The Industrial Emissions Directive (The European Parliament and the Council of the European Union, 2010) requires that (a) waste incinerators maintain a temperature of 850°C or greater after the last

injection of combustion air for a gas residence time of at least 2 seconds, (b) this temperature be at least 1100°C if the hazardous waste input contains greater than 1% of halogenated substances (as chlorine), and (c) temperature be continuously monitored at a location representative of the combustion chamber. An earlier version of this Directive also specified a minimum level of 6% oxygen (O_2) in the exhaust gas (Buekens, 2013). In order to maintain temperature above the minimum and prevent emissions in excess of emission limit values, incinerators are required to operate auxiliary burners and automatic waste feed cutoff systems (The European Parliament and the Council of the European Union, 2010). Furthermore, the Industrial Emissions Directive allows Member States to set alternate temperature requirements in incinerator permits provided that the other regulatory criteria are met. For example, the merchant hazardous waste incinerator in Antwerp, Belgium has a minimum temperature limit of 950°C (in place of the 1100°C value in the Directive) in its permit based on review of site-specific factors by the competent authority (Arcadis Belgium, 2019; Van Caneghem et al., 2025).

5.2 Combustion technology

The standard design for incinerating solid hazardous waste in Europe makes use of a rotary kiln as the primary combustion chamber (where solid wastes and liquid wastes are fed) followed by an afterburner as the secondary combustion chamber (where liquid wastes and fuel are fed) (Buekens, 2013). Solid waste feeds include batch-fed containerised waste which is carefully controlled to maintain steady-state conditions in the kiln and prevent transient emission peaks (Wood et al., 1989). With adequate temperature and solids residence time, the organic fraction of solid wastes (e.g., polymers) is converted to gaseous form in the kiln via pyrolysis (Lee et al., 1986; Pershing et al., 1993). Combustion of the resulting gases begins in the kiln and is completed in the secondary combustion chamber (Hitachi Zosen Inova AG, 2024). Rotary kilns can be operated in ashing mode to generate combustion solid residue as nonmolten ash or in slagging mode to generate combustion solid residue as slag (Niessen, 2010). In Europe, most rotary kilns operate in ashing mode (Villalba Weinberg et al., 2016). For ashing kilns, typical solids residence times range from 20 minutes to over 60 minutes (Niessen, 2010).

Rotary kiln incinerators are approved by the United Nations Environment Programme (UNEP) for environmentally sound destruction of solid, liquid, and gaseous fluorocarbon materials (Devotta et al., 2002). Full-scale testing in Japan demonstrated >99.99% destruction for mixtures containing 1.6 to 2.4% (by weight) of a range of chlorofluorocarbons in industrial waste with rotary kiln temperatures between 840°C and 920°C and secondary combustion temperatures of 710°C to 870°C (Urano et al., 1997). For incinerators dedicated to the destruction of fluorocarbons, it is generally necessary to provide a fuel source of hydrogen to enable complete decomposition to carbon dioxide (CO_2) and hydrogen fluoride (HF) (Rost, 1994). Since city gas (primarily CH_4) was only fed during one of the 12 tests in Japan, the hydrogen generated during combustion of the hydrocarbon-rich industrial waste was apparently sufficient to enable complete fluorocarbon decomposition. In routine long-term practice, fluorine levels in incinerator feeds are intentionally limited in order to minimize damage to silica-containing refractory lining the combustion chambers (DeLucia & Wolfe, 2000) and to silica-containing air pollution control equipment (Yang, 2000).

5.3 Combustion operating conditions

In Europe, hazardous waste incinerators generally operate with kiln (primary chamber) exit temperatures between 900°C and 1200°C (Neuwahl et al., 2019) and secondary combustion chamber temperatures between 1050°C and 1300°C (Buekens, 2013; Hitachi Zosen Inova AG, 2024). Consistent with the Industrial Emissions Directive summarised in section 5.1, these secondary combustion chamber temperatures are maintained for a gas residence time of 2 seconds (Hitachi Zosen Inova AG, 2024).

5.4 Post-combustion controls

Hot exhaust gas from the secondary combustion chamber flows through air pollution control equipment prior to emission to the atmosphere via a stack. Based on data compiled by Eurostat (https://ec.europa.eu/eurostat), roughly 60% of the hazardous waste incinerated in Europe is processed in facilities meeting the R1 energy efficiency standard (European Commission Directorate General-Environment, 2011). Hence, the corresponding incinerators route the hot exhaust gas through boilers to recover energy. The other hazardous waste incinerators in Europe (classified in Eurostat as D10) either quench the exhaust via direct contact with aqueous solution to reduce gas temperature as needed to accommodate downstream gas cleaning equipment (Neuwahl et al., 2019; Niessen, 2010) or cool the exhaust via waste heat boilers with recovery efficiencies that do not meet the R1 standard. As summarised in Annex 8.4 of the BAT Reference Document (Neuwahl et al., 2019), several hazardous waste incinerators practice selective non-catalytic NOx reduction where ammonia or urea is injected into the hot exhaust gas (800°C to 1000 °C) before cooling. NOx is controlled at other hazardous waste incinerators via selective catalytic reduction downstream at temperatures in the range of 170 °C to 250°C (Neuwahl et al., 2019). Particulates are removed from the cooled exhaust gas by electrostatic precipitators (ESPs) or baghouse filters. Most of the hazardous waste incinerators compiled in Annex 8.4 of the BAT Reference Document employ wet scrubbing with aqueous solution to remove acid gases (i.e., SO_2, HCl, and HF) from the exhaust. The remainder are equipped with either semi-dry scrubbing processes or dry scrubbers. In each type of scrubbing process, an alkaline reagent (i.e., calcium hydroxide, calcium oxide, calcium carbonate, sodium carbonate, sodium bicarbonate, or sodium hydroxide) neutralises the acid gas (Neuwahl et al., 2019). Consequently, inorganic fluoride present in the exhaust gas (e.g., HF) would be converted to calcium fluoride (CaF_2) or sodium fluoride (NaF), depending on the alkaline reagent in use, and report to the solid residual from the particulate control device or from treatment of wet scrubber effluent, as applicable. This conversion and removal ensures compliance with the HF emission limits specified in the Industrial Emissions Directive (The European Parliament and the Council of the European Union, 2010) and the BAT Reference Document (Neuwahl et al., 2019).

5.5 Organofluorine fate

In summary, end-of-life fluoropolymers in the feed to a hazardous waste incinerator are converted into gaseous form that reacts with the other gases present (e.g., O_2), and the resulting inorganic fluoride and other combustion products proceed through the air pollution control system to remove the inorganic fluoride.

5.5.1 Incineration chemistry

PTFE serves here a model fluoropolymer because it accounts for over half of the fluoropolymers market (E. Zhang et al., 2016) and is more thermally stable than other commercial fluoropolymers (Dolatabad et al., 2025; Giannetti, 2005). With PTFE as an example, the pyrolysis of fluoropolymer into gaseous form can be described in chemical terms by equation 5-1 based on the authoritative review of Puts, Crouse, and Ameduri (2014).

$$(C_2F_4)_n \xrightarrow{\text{heat}} :CF_2 \qquad (5\text{-}1)$$

The presence of excess water vapour (H_2O) minimises the recombination of these difluorocarbene ($:CF_2$) free radicals into tetrafluoroethylene (C_2F_4) or larger fluorocarbons (Filatov et al., 2011). This is

important because water (H_2O) is abundant in the reaction atmosphere as a main combustion product (along with CO_2) and a component of certain waste feeds (Lee & Huffman, 1989). Under these dilute conditions representative of routine long-term practice (noted in section 5.2) and at typical kiln temperatures (noted in chapter 5.3), $:CF_2$ radicals are expected to react with the oxygen in combustion air to form carbonyl fluoride (CF_2O) via the reaction in equation 5-2 (Burgess et al., 1996).

$$:CF_2 + O_2 \rightarrow CF_2O + O: \quad (5\text{-}2)$$

The resulting CF_2O is expected to hydrolyse to HF in the incineration system (including wet scrubbing) according to the net reaction in equation 5-3 (Francisco, 1993).

$$CF_2O + H_2O \rightarrow CO_2 + 2HF \quad (5\text{-}3)$$

Although the ~~(~~C_2F_4~~)~~ repeating units of PTFE are thereby expected to transform into HF during incineration, it is also necessary to consider the fate of the $–CF_3$ groups at each end of the polymer chain noted by Henry et al. (2018). During PTFE incineration where large quantities of other organofluorine materials such as aqueous film-forming foam (AFFF) concentrate are concurrently fed, the availability of F· atoms and $\cdot CF_3$ free radicals can increase considerably. In this case, the $\cdot CF_3$ free radicals stemming from the PTFE end groups are more likely to form some CF_4 or C_2F_6 as products of incomplete combustion (PICs) via the side reactions in equations 5-4 and 5-5 (Burgess et al., 1996).

$$\cdot CF_3 + F\cdot \rightarrow CF_4 \quad (5\text{-}4)$$

$$\cdot CF_3 + \cdot CF_3 \rightarrow C_2F_6 \quad (5\text{-}5)$$

However, incinerators can prevent formation of CF_4 and C_2F_6 as PICs by ensuring sufficient input of (a) hydrogen sources such as natural gas (primarily CH_4) or hydrocarbon-rich wastes or (b) other fluorine acceptors such as lime (Blotevogel et al., 2026). Such prevention is important as once present, highly stable CF_4 requires a 1-second gas residence time at 1441°C to decompose (Tsang et al., 1998) and CF_4 and C_2F_6 are potent greenhouse gases (Greenhouse Gas Protocol, 2024) and thus environmentally relevant.

Bench-scale experiments (Difelice & Ritter, 1996; Romelaer et al., 2001) have confirmed that perfluorinated compounds are not formed at temperatures above 650°C in the presence of hydrogen.

As part of routine practice, hazardous waste incinerators blend waste feeds to maintain low halogen concentrations and ensure consistent operation (Niessen, 2010). At routine dilute conditions, $\cdot CF_3$ free radicals would be expected to react with H· atoms and O· atoms respectively via the reactions in equations 5-6 and 5-7 (Burgess et al., 1996).

$$\cdot CF_3 + H\cdot \rightarrow :CF_2 + HF \quad (5\text{-}6)$$

$$\cdot CF_3 + O\cdot \rightarrow CF_2O + F\cdot \quad (5\text{-}7)$$

The reaction products in equations (5-6) and (5-7) would be converted to HF via the reactions in equations 5-2 and 5-3.

In summary, it is predictable that

- HF is the dominant fluorinated product from combustion of fluoropolymer pyrolysis gas in hazardous waste incinerators and
- this HF reports to CaF_2 or NaF in the solid residue from flue gas treatment.

While formation of CF_4 and C_2F_6 as PICs from hazardous waste incineration of fluoropolymers may be possible in the presence of excess quantities of other organofluorine materials, the reaction chemistry does not predict their formation during routine operation. Assessing the potential for these and other potential fluorinated PICs requires evaluation of recent data from large-scale PFAS stack testing under hazardous waste incinerator conditions.

5.5.2 Incinerator emission testing

Recently, emission test programmes have determined PFAS emissions from three industrial (full-scale) hazardous waste incinerators. While the focus of this hazardous waste incinerator testing largely has been on the destruction of PFAS-rich streams such as AFFF concentrate, it is possible to estimate the organofluorine fate of fluoropolymers from the stack testing results during baseline or routine operations when high levels of non-polymer PFAS were not intentionally added.

Table 5-1 presents basic descriptive information (e.g., temperatures, residence times) for the three hazardous waste incinerators (one column for each) as context for also presenting facility-specific OTM-45 mass emission rates and OTM-50 (or similar technique) emission concentrations. OTM-45 is a sampling and analysis method developed by EPA in the U.S. to quantify stack emissions of individual water-soluble, semi volatile, polar PFAS compounds such as perfluoroalkyl carboxylic acids and perfluoroalkyl sulfonic acids with 4 or more carbon atoms on the perfluoroalkyl chain (EPA, 2025b). OTM-50 is a separate sampling and analysis method (also developed by EPA in the U.S.) to quantify stack concentrations of volatile fluorocarbon compounds such as C1 to C8 perfluorocarbons (including CF_4 and C_2F_6) because they are not compatible with the techniques employed by OTM-45 (Wallace et al., 2025). The perfluorocarbons and certain other OTM-50 compounds are potent greenhouse gases (Greenhouse Gas Protocol, 2024). Additionally, the table presents calculated fluoropolymer input rates based on an estimate for the concentration of fluoropolymer in European hazardous waste. In turn, this calculated input rate is used with the tabulated OTM-45 emission rates to compute an emission factor (g OTM-45 PFAS/tonne fluoropolymer incinerated) for each facility. The table also includes a fourth column with results from KIT Brenda for reference because Gehrmann et al. (2024) conducted large pilot-scale testing there with fluoropolymers intentionally spiked into the incinerator feed. The table concludes with stack concentrations of volatile fluorocarbon compounds (e.g., via OTM-50) and comparison to corresponding CO_2 stack concentrations in terms of contribution to global climate change.

Table 5-1: PFAS Testing Results and Emission Factors for Hazardous Waste Incineration

Facility Test Report(s)	units		Crisenbery et al., 2024; EA Engineering Science and Technology Inc, 2021; Troxler et al., 2025		AECOM, 2024; Labaye et al., 2025	Hofman et al., 2025; Van Caneghem et al., 2025		Aleksandrov et al., 2019; Gehrmann et al., 2024
Facility			Clean Harbors		Veolia	Indaver		KIT Brenda
Location			Aragonite, Utah, USA		Port Arthur, Texas, USA	Antwerp, Belgium, EU		Karlsruhe, Germany, EU
Scale			Industrial		Industrial	Industrial		Pilot
Kiln temperature	°C		1187		881	not reported		894
Solids residence time in kiln	min		~60		~60	30 – 60		~60
Secondary combustion chamber temperature	°C		1128		1120	1035		1095
Gas residence time in secondary chamber	sec		2 - 3		2.3	2		2
Combustion exhaust gas cooling	---		spray dryer		quench tower	boiler		boiler
Acid gas removal	---		wet scrubber: Na_2CO_3		wet scrubber: NaOH	wet scrubber: lime		wet scrubber
Stack CO_2 (dry basis)	%		8.51		9.3	9		7.9
Testing Condition	---		baseline (no AFFF)		baseline (no AFFF)	routine operation		spiked with fluoropolymer
Average fluoropolymer concentration in EU haz waste	kg/t		1.12		1.12	1.12		not applicable
Hazardous waste feed rate to incinerator	t/hr		6.12		8.75	8		not applicable
Fluoropolymer (FP) mass input rate	kg/hr		6.87		9.83	8.99		0.32
Stack total OTM-45 PFAS	g/hr		1.47E-03		3.46E-03	4.91E-03		4.60E-07
Stack PFAS levels influenced by scrubber water supply			No		Yes	No**		No
Emission factor, g OTM-45 PFAS/tonne fluoropolymer incinerated			0.21		0.35	0.55		1.44E-03
Stack CF_4 via OTM-50	µg/m³	<	1.85	<	4.95	not measured	<	40***
Stack C_2F_6 via OTM-50	µg/m³	<	0.14	<	1.80	not measured	<	30***
Stack CHF_3 via OTM-50	µg/m³	<	0.29	<	1.16	not measured	<	20***
Other stack volatile F compounds via OTM-50	µg/m³		1.83	<	1.94	not measured	<	30***
Main other stack volatile F compounds detected			chlorofluorocarbons		fluoroether E-1	not applicable		not applicable
CF_4 + C_2F_6 + CHF_3 Climate Impact (as CO_2e)	µg/m³	<	1.96E+04	<	7.58E+04	not applicable	<	9.59E+05
Climate Impact$_{CO2}$ / Climate Impact$_{CF4+C2F6+CHF3}$		≥	8505	≥	2409	not applicable	≥	162

*** Calculated from information in Gehrmann et al., 2024 and Aleksandrov et al., 2019 via mass balance with standard combustion stoichiometry (Witte, 1992).**

**** OTM-45 results for Indaver Antwerp are from stack testing after upgrades to treatment process for scrubber water supply.**

***** Since OTM-50 was not available at the time of their study, Gehrmann et al., 2024 analysed canister samples via a custom GC-MS method described in their paper.**

5.5.2.1 Emissions of water-soluble PFAS

The emission factor shows how much water-soluble PFAS is formed and emitted for each tonne of fluoropolymer incinerated. This allows to evaluate the significance of the emissions and to compare the test cases on a consistent basis. The emission factors in Table 5-1 for water-soluble PFAS (i.e., OTM-45 PFAS) from each incinerator are computed in three steps.

In a first step, a conservative estimate for the concentration of fluoropolymer in the hazardous waste input is calculated for the three industrial hazardous waste incinerators (where fluoropolymers were not intentionally added). This estimate is made using the 2020 annual mass flow of fluoropolymer to hazardous waste incineration for the European Union plus Norway, Switzerland, and the United Kingdom + 3) in Figure 4-1 (11.74 kt/year) and the European Union (EU-27) annual quantity of hazardous waste to incineration from Eurostat (https://ec.europa.eu/eurostat) for the same year. The EU-27 annual quantity (10.45 Mt/year) is the sum of hazardous waste to R1 facilities (6.11 Mt/year) and to D10 facilities (4.34 Mt/year); see chapter 5.4. The resulting estimate for the average concentration of fluoropolymer in European hazardous waste is 1.12 kg/t (=11.74 kt fluoropolymer ÷ 10.45 Mt hazardous waste). This is a conservative estimate because the mass of fluoropolymer corresponds to a larger economic zone than for which Eurostat reports. In the absence of more specific information (which is not included in full-scale emission test reports), the 1.12 kg/t value is useful to calculate emission factors for mass of PFAS emissions per mass of fluoropolymer input. For the three hazardous waste incinerators, this estimated concentration is combined with the hazardous waste feed rate to the kiln to estimate the fluoropolymer mass input rate.

In a second step, mass rates for total OTM-45 PFAS emissions from the four facilities are compiled in Table 5-1 and discussed in this paragraph. Note that the series of stack tests at Indaver Antwerp by (Hofman et al., 2025) was performed during routine operation without intentional PFAS spiking into the waste feeds and at the low end of the secondary combustion chamber temperature range in chapter 5.3. Targeting 49 individual water-soluble PFAS compounds in the C4 to C18 range, stack sampling via OTM-45 traps compounds in water and on XAD resin for off-line analysis via solid-phase extraction and liquid chromatography with tandem mass spectrometry (EPA, 2025b). Due to various challenges associated with the analysis of trifluoroacetic acid (TFA) and other ultrashort chain fluorinated acids (with 3 or fewer carbon atoms on the perfluoroalkyl chain) via the techniques employed by OTM-45 (Gauthier et al., 2025), TFA is not an OTM-45 target analyte. Based on pilot-scale incineration testing by (Mattila et al., 2024) with specialised online analytical equipment, TFA emissions are expected to be no higher than perfluorobutanoic acid (PFBA) emissions that are included in the total OTM-45 PFAS emissions listed in Table 5-1. The emission rates presented for total OTM-45 PFAS are very low, and many of the individual compound results were reported as not detected. Values for total OTM-45 PFAS in the table were taken directly from the referenced papers, relying on how non-detects were reported by the original authors. Non-detects were assumed to be present at the detection limit by both EA Engineering Science & Technology (2021) and Labaye et al. (2025) and to be zero by Hofman et al. (2025). Gehrmann et al. (2024) presented their compound-specific OTM-45 results in two ways with one figure assuming non-detect to be zero and a second figure assuming non-detect as present at half the detection limit. Where OTM-45 compounds were detected, the test reports pointed to two non-combustion causes in particular:

a. The authors of the reports summarised in Table 5-1 observed external contamination of either sampling or analytical equipment. For example, in their test report for Clean Harbors Aragonite (first column in Table 5-1), EA Engineering Science & Technology (2021) stated "PFBA, the compound with the highest calculated emission rate, was present in the method blank (XAD resin media blank)". When the same facility underwent further OTM-45 stack testing reported by Troxler et al. (2025) (that did not present OTM-45 results for baseline conditions), elevated

levels of HFPO-DA found in sampling trains (including the blank sampling train not inserted in the stack) were attributed to contaminated train components (Shields, 2025).

b. Two of the reports noted that PFAS-contaminated supply water to the wet scrubbers of the air pollution control system (downstream of combustion) influenced the emission results. For example, Hofman et al. (2025) reported a significant decrease in OTM-45 PFAS emissions following upgrades to the treatment process for the scrubber supply water. As noted on Table 5-1, the OTM-45 emissions from Indaver Antwerp (third column in the table) were measured after these upgrades were implemented.

In a third and final step to compute an emission factor (g OTM-45 PFAS/tonne fluoropolymer incinerated) for each facility, the tabulated OTM-45 mass emission rates are divided by the fluoropolymer mass input rate (estimate calculated in step 1 except for KIT Brenda). Even with the influence of external contamination of sampling or analytical equipment and contaminated scrubber supply water, the emission factor in each case is less than 1 g OTM-45 PFAS per tonne of fluoropolymer incinerated. Note that the emission factors in Table 5-1 are likely to be conservative estimates because fluoropolymers are not the only non-AFFF organofluorine material commonly in the feed to hazardous waste incinerators. For example, 20% of pharmaceuticals currently on the market contain organofluorine (Caron, 2020), and Finland and Denmark require unused or expired medicines be disposed of via hazardous waste incineration (OECD, 2022). Nonetheless, if one were to compute the emission factor for a compound X incinerated to 99.9999% destruction for reference, the corresponding emission factor for that compound would be 1 g compound X per tonne of compound X incinerated. In other words, when 1 tonne of compound X is incinerated at 99.9999% destruction efficiency, only about 1 gram of compound X remains in the emissions.

5.5.2.2 Emissions of volatile fluorinated compounds

Stack concentrations of volatile fluorinated compounds (via OTM-50 or similar technique) are also compiled in Table 5-1 (where reported for the facility) and compared to the facility's CO_2 stack concentration based on contribution to global climate change. Targeting 30 individual volatile fluorinated compounds in the C1 to C8 range, sampling with OTM-50 collects stack gas in ceramic lined stainless-steel canisters for off-line analysis via gas chromatography/mass spectrometry (EPA, 2025c; Wallace et al., 2025). Table 5-1 highlights emissions for three of the most potent greenhouse gases (CF_4, C_2F_6, and CHF_3). The table also notes the total concentration of the remaining volatile fluorinated compounds and the identity of the main volatile fluorinated compound detected. These emission concentrations are very low, and many of the individual compound results were reported as non-detect. The less than sign (<) is used in the table to note where some or all of the values used in determining the tabulated average (across multiple test runs) were not detected. The lowest volatile fluorinated compound concentrations in the table correspond to analysis of Clean Harbors Aragonite OTM-50 samples performed by EPA in their Research Triangle Park laboratory (Troxler et al., 2025). Labaye et al. (2025) noted that the high hydrogen-to-fluorine ratio in the secondary combustion chamber raised doubt about the accuracy of CF_4 detection during one of the Veolia Port Arthur (second column) in Table 5-1 baseline runs. Additionally, Labaye et al. (2025) noted that the fluoroether E-1 detected in one baseline run was likely to be the result of analytical laboratory contamination. Similarly, Shields (2025) noted that the chlorofluorocarbons detected at Clean Harbors Aragonite are \"common refrigerants\" found in the analytical laboratory. Since most of the volatile fluorinated compounds in Table 5-1 (18 of 30) are potent greenhouse gases, the impact of corresponding emission concentrations can be assessed by comparison to CO_2 considering the global warming potential (GWP) values for these compounds from the IPCC Six Assessment Report (AR-6). Although the AR-6 GWP values for three of the most potent global warming compounds (CF_4 + C_2F_6 + CHF_3) range from 7380 to 14,600 times greater than CO_2 (Greenhouse Gas

Protocol, 2024), the Climate Impact (as CO_2e) of their incineration emission here is very low in comparison to CO_2. See equation 5-8.

$$\text{Climate Impact} = \sum\left[(\text{mass concentration})_i \times GWP_i\right] \quad (5\text{-}8)$$

For example, if the less than values (indicative of mainly non-detect values) for CF_4 + C_2F_6 + CHF_3 emission concentrations from Clean Harbors Aragonite in Table 5-1 are assumed to be present, the Climate Impact of these three compounds would be a factor of 7780 times less than the Climate Impact of this incinerator's CO_2 emission. It needs to be considered that this factor would have been even higher for each facility if the facility's analytical laboratory had achieved lower detection limits.

5.5.3 Broader implications

While the emission factors estimated herein are based on testing at four sites, each facility used the same rotary kiln technology, which is widely used at hazardous waste incinerators across Europe (see chapter 5.2). The results can therefore be considered broadly relevant to current operating practices at hazardous waste incineration plants in Europe.

Collecting additional data through a structured sampling program (Cochran, 1977) would reduce uncertainty associated with the PFAS emission factors estimated herein. France has begun such a sampling program with a three-year timeline (2025 – 2028) for analysing PFAS emissions to air from both hazardous waste incinerators and municipal WTE plants (Volcovschi, 2025). Recently collected PFAS emission data from hazardous waste incinerators are consistent with the results presented in section 5.5. One example is a comprehensive three-year test program being conducted at a full-scale rotary kiln incinerator Germany (Holm et al., 2026). OTM-50 results from this program's initial 2025 testing campaign show no detected emissions of CF_4 or other volatile fluorinated compounds under any conditions. OTM- 45 results were not yet available at the time of the January 2026 Berlin Waste Conference. Another is recent testing at the Indaver merchant rotary kiln incinerator in Hamburg, Germany that demonstrated PFAS destruction efficiency greater than 99.9999% (Grote et al., 2026).

6. Municipal waste-to-energy combustion

As described in Figure 4-1, 22% of annual end-of-life fluoropolymer mass in 2020 (5.15 kt) flowed to municipal waste-to-energy (WTE) combustion. The following chapter summarises information on the fate of fluoropolymers in European municipal WTE plants.

Key messages

- Fluoropolymers used in consumer and some other applications report to municipal solid waste (MSW) at end of life. Much of these end-of-life fluoropolymers are managed via municipal WTE combustion.
- A conservative estimate for the average concentration of fluoropolymer in the MSW feed to municipal WTE plants in Europe is calculated to be 51 g fluoropolymer/t MSW (0.005%).
- Moving grate combustion accounts for over 92% of municipal WTE combustion design capacity in Europe. Municipal WTE plants operate above minimum standards specified in the European regulations. In Europe, typical moving grate WTE plant operating conditions are 2 seconds of gas residence above 1100°C in the furnace.
- Due to harsh conditions in the furnace combustion zone (where thermocouples do not survive), municipal WTE plants normally monitor temperature at lower-temperature location (e.g., furnace ceiling) that has been correlated to the much higher combustion zone temperature.
- Municipal WTE plants are approved by United Nations Environment Programme for environmentally sound destruction of fluorocarbon-containing solids.
- A conservatively estimated emission factor is computed as less than 1 g water-soluble PFAS/tonne fluoropolymer incinerated (0.0001%), even including the effect of other organofluorine material input to municipal WTE combustion and external contamination that may have affected stack testing results. This is comparable to a destruction efficiency of greater than **99.9999%**.
- WTE combustion chemistry predicts that (a) hydrogen fluoride (HF) is the dominant fluorinated product from combustion of the gases evolved from fluoropolymer pyrolysis and (b) this HF reports to calcium fluoride (CaF_2) or sodium fluoride (NaF) in the solid residue from flue gas treatment.
- Three separately-measured volatile fluorinated compounds (CF_4 + C_2F_6 + CHF_3) are recognised greenhouse gases. The Climate Impact of the emissions of these three compounds are shown to be thousands of times less than the municipal WTE plant's CO_2 emission concentration (assuming presence at the detection limits for non-detect values) under routine operating conditions.
- Generation of CF_4 from municipal WTE combustion requires extreme conditions unrepresentative of typical municipal WTE plant operation and unrelated to end-of-life fluoropolymers in MSW. An example of such conditions is intermittently feeding containers of liquid providing both (a) ·CF_3 free radical sources and (b) elevated hydrocarbon content. As an inert gas, virtually insoluble in water, CF_4 does not fit the toxicity profile generally associated with PFAS.

Municipal solid waste (MSW) is expected to contain end-of-life fluoropolymers that have been used in consumer applications (e.g., pipe thread sealant tape, nonstick cookware) (Drobny & Ebnesajjad, 2023). According to the Confederation of European Waste-to-Energy Plants (CEWEP) (Confederation of European Waste-to-Energy Plants (CEWEP), 2022), 27% of MSW was treated via municipal WTE combustion in EU27 + 3 at roughly 500 municipal WTE plants during 2020 (same study frame used by Conversio Market & Strategy, 2023). Additionally, fluoropolymers used in automotive applications (e.g., seals, brake system components) at end of life generally report to automotive shredder residue (ASR) much of which in turn is directed to municipal WTE combustion (Conversio Market & Strategy, 2023). Municipal WTE combustion plants across Europe are strictly regulated to control emissions to the environment (Neuwahl et al., 2019).

6.1 Relevant Regulations

The Industrial Emissions Directive (The European Parliament and the Council of the European Union, 2010) requires that

- municipal WTE combustion plants be operated in a controlled manner with at least 2 seconds of gas residence time above 850˚C after the last injection of combustion air,
- this temperature be continuously monitored at a location representative of the combustion chamber, and
- municipal WTE plants operate auxiliary burners and automatic waste feed cutoff systems in order to maintain temperature above the minimum and prevent emissions in excess of emission limit values. As noted for hazardous waste incinerators in chapter 5.1, an earlier version of this Directive also specified a minimum level of 6% oxygen (O_2) in the exhaust gas (Buekens, 2013).

The fraction of MSW treated via municipal WTE combustion is expected to increase over time due to the influence of EU policies that promote landfill diversion and use of renewable energy (Scarlat et al., 2019).

Recently adopted national regulations in some EU Member States (e.g., Germany) show a shift toward sewage sludge mono-incineration to facilitate phosphorus recovery (Egle et al., 2023). Consequently, some municipal waste-to-energy (WTE) plants are expected to experience higher combustion temperatures if the co-incineration of sewage sludge is reduced or discontinued, due to the associated reduction in water introduced to the combustion process.

6.2 Combustion technology

A few different furnace designs are used to recover energy via MSW combustion in Europe (Neuwahl et al., 2019). Historically, the International Solid Waste Association (ISWA) compiled these different MSW combustion technologies. Prior analysis of the latest ISWA compilation (2013) shows that moving grate technology accounts for about 90% of municipal WTE combustion design capacity in Europe (Lu et al., 2017; Makarichi et al., 2018). The latest ISWA compilation (ISWA Working Group on Energy Recovery, 2013) has been updated to remove closed plants and add newly built plants based on review of the Coenrady database (http://www.coenrady.com), equipment provider reference lists, facility websites, periodicals, and other public information. This confirmed the combustion technology in use at plants accounting for 86% of total WTE combustion design capacity in Europe (EU27 + 3). Table 6-1 presents the compilation of these plants by technology type and corresponding fraction of design capacity.

Table 6-1: Municipal WTE combustion technologies in EU27 + 3 by design capacity in 2025

Technology type	% of design capacity
Moving grate	92.5
Fluidised bed	5.2
2-stage Moving grate	0.9
2-stage Fluidised bed	0.7
Oscillating kiln	0.4
Rotary kiln	0.3

This compilation confirms that combustion of MSW on a moving grate accounts for over 90% of municipal WTE design capacity. Thermal conversion of the organic fraction of solid wastes (e.g., polymers) on the grate involves a sequence of drying, devolatilization, char gasification, and char burning that collectively produce gas for gas-phase combustion above the grate (Giraud et al., 2022). The typical solids residence time for moving grate plants is 60 minutes (Klinghoffer et al., 2013). In 2-stage moving grate plants, MSW is gasified over a grate in the first stage, and the resulting gas is combusted in the second (Arena,

2012). As with 2-stage moving grate plants, the MSW feed to fluidised bed plants is first processed via shredding and ferrous metal removal (Kalogirou, 2018). Consistent with fluidised bed technology constituting the standard design for sewage sludge incineration (Buekens, 2013), many fluidised bed municipal WTE plants have traditionally co-incinerated sewage sludge. In 2-stage fluidised bed plants, shredded MSW is gasified in a fluidised bed reactor, and the resulting gas is combusted in a second chamber (Consonni & Viganò, 2012). Although misclassified at times as a rotary kiln (Nixon et al., 2013), the oscillating kiln features a partly cylindrical and partly conical refractory-lined vessel that oscillates back and forth over an amplitude of 210° and discharges combustion gas into a tranquilization chamber (Gonnord et al., 1989; Grillo, 2013). Like oscillating kiln plants, rotary kiln plants combust MSW as received without preprocessing. The few rotary kiln municipal WTE plants in Europe use the same basic kiln-afterburner design described in section 5.2.

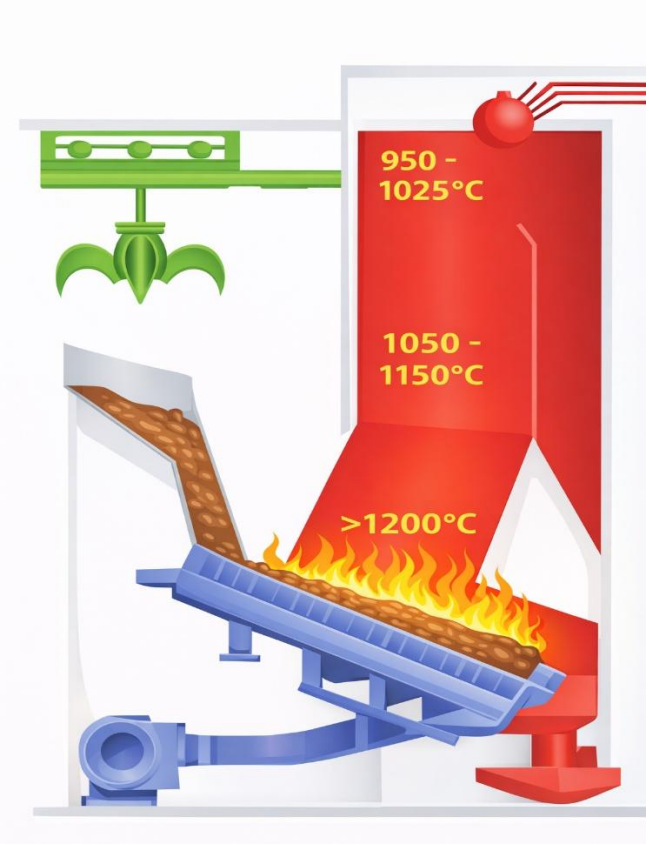
Municipal WTE plants are approved by the United Nations Environment Programme (UNEP) for environmentally sound destruction of fluorocarbon-containing solids, i.e., foam insulation that used chlorofluorocarbons as blowing agents (Devotta et al., 2002). Full-scale testing at a moving grate municipal WTE plant prior to 1994 demonstrated 99.998% destruction of chlorofluorocarbon-11 (CFC-11) contained in polyurethane foam (used in refrigerators at that time) at a mean furnace temperature of 845°C (Rittmeyer et al., 1994). During this test program, flue gas (prior to air pollution control) HF concentration increased to 50 mg/m^3 from a baseline level of 6 mg/m^3, indicating that the fluorocarbon input rate was much higher than normal operation. For reference, municipal WTE flue gas HF concentration (at inlet to air pollution control system) is typically less than 10 mg/m^3 in Europe (Jurczyk et al., 2016a; Vehlow, 2015)

6.3 Combustion operating conditions

In practice, European municipal WTE plants generally run with more time at temperature in the furnace than the regulatory minimum values in section 6.1 in order to complete gas-phase reactions before reaching colder downstream boiler surfaces (Hulgaard & Vehlow, 2010). Furthermore, municipal WTE plants in Europe operate with a "safety margin" (e.g., well above the minimum limits) to always maintain compliance with operating requirements when coping with the inhomogeneous nature of municipal solid waste (Schucht et al., 2001). Figure 6-1 displays a representative temperature profile across the furnace of a moving grate municipal WTE plant from Beckmann and Scholz (2003). As the figure shows, the typically monitored ceiling temperature (950 - 1025°C) is hundreds of degrees lower than the gas temperature above the grate (>1200°C).

Table S1 of a recent report by Johansson et al. (2024) report suggests that 9 of 27 unnamed municipal WTE plants in Sweden have "incineration temperatures" as low as the interval between 850 and 899°C. Review of this report indicates that as many as 4 of these 9 plants may have operated fluidised bed units that are designed to operate at lower temperatures than moving grate plants. The authors appear to have reported monitored ceiling temperatures of 5 or more moving grate plants that underrepresent actual conditions in the combustion zone of the WTE furnaces they sampled.

In accordance with national or local environmental regulations implementing the Industrial Emissions Directive, WTE plants are required to conduct and submit time at temperature studies to the competent authority for review, and the competent authority reviews the resulting reports. These studies involve a combination of measurements and calculations to correlate key parameters to process variables (e.g., furnace ceiling temperature) that are routinely measured (Costa et al., 2012). Such correlation is necessary because thermocouples do not survive the harsh conditions of the WTE furnace combustion zone (The Babcock & Wilcox Company, 2005). Consequently, the temperature monitor used to comply with the Industrial Emissions Directive (The European Parliament and the Council of the European Union, 2010) normally displays a temperature reading that is much lower than the actual combustion zone temperature.



* Temperature values from Figure 3.24 in (Beckmann & Scholz, 2003)

Figure 6-1: Typical temperature profile for Moving Grate municipal WTE plant in Europe following (Beckmann & Scholz, 2003)*

Table 6-2 summarises available literature to show the range of actual temperatures and corresponding gas residence times at operating municipal WTE plants in Europe.

Table 6-2: Typical Values for European Municipal WTE Plant Combustion Operating Conditions

		Gas-phase Combustion Zone		
Technology type	Technology Provider	Temperature (T) (°C)	Gas Residence Time at T (sec)	Reference(s)
Moving grate	Martin	1195[a]	2	(Arpino et al., 2015)
Fluidised bed	Valmet[b]	927[c]	2.5[c]	(Murphy, 1999)
2-stage Moving grate	Energos	1000	2	(Ellyin & Themelis, 2011; Energos, 2025)
2-stage Fluidised bed	Kobelco	1200	1.9[d]	(Hosoda et al., 2008; NSC, 2020)
Oscillating kiln	Paprec[e]	1040	2	(Gonnord et al., 1989)
Rotary kiln	Hafner	950	2	(Hafner Energy from Waste Srl, 2006)

a Average of 5 values in Figure 7 of the referenced paper.

b At the time of the referenced paper, the name of the technology provider for the fluidised bed plant in Italy was Energy Products of Idaho.

c Temperature and gas residence time are for the freeboard. The bed temperature of a fluidised bed WTE plant is generally lower than the freeboard temperature.

d The gas residence time is estimated from gas velocity in melting furnace (18 m/sec) and height of steel structure above melting furnace (37 m, allowing for 1 m clearance above and below melting furnace): (37-2)/18 = 1.94 sec. Therefore, gas residence for this furnace above 850°C is much greater than 2 sec especially when one considers the residence time in the boiler which follows the melting furnace.

e At the time of the referenced paper, the name of the technology provider was Laurent Bouillet.

Fluidised bed furnaces operate at lower temperatures by design (Buekens, 2013) because this technology is able to achieve efficient combustion via uniform mixing and heat transfer (Van Caneghem et al., 2012).

6.4 Post-combustion controls

Municipal WTE combustion gas passes through boiler equipment to recover energy and to cool the gas before entering the air pollution control system (Hulgaard & Vehlow, 2010). However, many municipal WTE plants practice selective non-catalytic NOx reduction (as described in chapter 5.4) before such cooling (Vehlow & Dalager, 2010). Other municipal WTE plants employ selective catalytic reduction (SCR) for NOx control (Vehlow, 2015). Ramboll experience indicates that SCR is accomplished at municipal WTE plants in the 180°C to 280°C temperature range. Baghouse filters are widely installed for particulate control at municipal WTE plants equipped with dry or semi-dry scrubbing, and electrostatic precipitators are commonly in place for the same purpose at plants with wet scrubbers (Vehlow, 2015; Vehlow & Dalager, 2010). Acid gases (i.e., SO_2, HCl, and HF) are removed from municipal WTE flue gas by wet, semi-dry, or dry scrubbing (Jurczyk et al., 2016b). Commonly used in Northern and Central Europe, wet scrubbing is usually performed in two stages with acidic scrubbing in the first stage and alkaline scrubbing in the second, where calcium carbonate, calcium hydroxide (lime), and sodium hydroxide are the typical alkaline reagents (Vehlow & Dalager, 2010). Both semi-dry scrubbing and dry scrubbing are performed in a single stage (Vehlow, 2015) with lime and sodium bicarbonate as the most common reagents (Vehlow & Dalager, 2010). Depending on the alkaline reagent employed, inorganic fluoride present in the flue gas would be converted to calcium fluoride (CaF_2) or sodium fluoride (NaF) and removed via the particulate control equipment or wet scrubber effluent treatment system, as applicable.

6.5 Organofluorine fate

As in hazardous waste incinerators (see chapter 5.5), the organofluorine fate of end-of-life fluoropolymers in the feed to municipal WTE plants is the combination of CaF_2 or NaF (depending on alkaline reagent used in acid gas scrubbing) and potential fluorinated PICs.

6.5.1 WTE combustion chemistry

Reactions 5-1 through 5-3 and 5-6 through 5-7 are also expected to occur during pyrolysis and combustion of PTFE (as a model fluoropolymer). Consequently, PTFE is expected to transform into HF and CO_2 in the furnace of a municipal WTE plant. From a chemistry perspective, the principal difference between hazardous waste incineration of fluoropolymers and municipal WTE combustion of fluoropolymers is the source of the hydrogen.

In municipal WTE plants, there are two major hydrogen sources. First, wood is a component of MSW in Europe (Hulgaard & Vehlow, 2010), and wood contains over 4.5% hydrogen (Witte, 1992). Furthermore, roughly half of MSW is made up of plant-based lignocellulosic materials, and pyrolysis of this lignocellulose (under conditions above the grate of municipal WTE furnace) supplies methane, methanol, and hydrogen in the reaction atmosphere above the grate (Giraud et al., 2022). Additional hydrogen is generated through pyrolysis of common plastics in MSW (e.g., high density polyethylene) as well as through the water-gas shift reaction in equation 6-1 (Giraud et al., 2022).

$$CO + H_2O \rightleftharpoons H_2 + CO_2 \quad (6\text{-}1)$$

Measurements at full-scale municipal WTE plants in Europe confirm a large supply of hydrogen sources above the grate. Dos Santos and Collin (1992) reported 6 to 16% H_2 and 1.8 to 2.2% CH_4 above the grate at a municipal WTE plant in Sweden. Waldner et al. (2013) reported 5% H_2 above first half of the grate at a municipal WTE plant in Germany.

As with hazardous waste incineration, it is predictable that HF is the dominant fluorinated product from combustion of fluoropolymer pyrolysis gas in municipal WTE plants due to the availability of hydrogen sources in the combustion zone and this HF reports to CaF_2 or NaF in the solid residue from flue gas treatment. Although PICs such as CF_4 and C_2F_6 are not expected to form during routine operation, assessing the potential for fluorinated PICs can be evaluated based on recent data from PFAS stack testing under municipal WTE combustion conditions.

6.5.2 WTE combustion emission testing

Recently, emission test programs have measured PFAS emissions from three industrial (full-scale) municipal WTE plants in Europe. Table 6-3 summarises the results of these test programs along with available descriptive information for the three municipal WTE plants. The first column presents testing at Umea Energi in Sweden reported by Björklund et al. (2023). Björklund et al. employed a modified version of EN 1948:1 to report emission concentrations for 18 water-soluble PFAS. The second column presents information available from testing by the Swedish Environmental Research Institute (IVL) (Strandberg et al., 2025) at a WTE plant (called Plant A) in Sweden for which half of the fuel input is MSW. Strandberg et al. conducted stack sampling with both EN 1948:1 and OTM-45 to collect concentration data for 54 water-soluble PFAS. In doing so, they demonstrated roughly similar results for total water-soluble PFAS via the two stack sampling methods. The third and fourth columns present results from testing at Gemeinschaftskraftwerk Schweinfurt (GKS) in Germany. In both cases, GKS adapted OTM-45 to report emission concentrations for 22 water-soluble PFAS and used OTM-50 to sample the stack for volatile fluorinated compounds. The third column contains GKS results for their reference case burning only MSW. The fourth column contains GKS results for testing where the MSW feed was spiked with large quantities of fluoropolymers and other organofluorine materials. Except for feed spiking during testing in the fourth column, each column describes testing conducted under routine municipal WTE plant operating conditions. Note that results from comprehensive PFAS testing at a municipal WTE plant in Florida (EPA, 2025a) are not included herein because EPA had not published the report of this testing prior to March 2026. In each column, Table 6-3 includes descriptive information for the plant, fluoropolymer mass input rate, stack total water-soluble PFAS mass emission rate, calculated emission factor (g water-soluble PFAS/tonne fluoropolymer incinerated), OTM-50 results (where measured), and calculated Climate Impact (using equation 5-8) to assess contribution to global climate change for three of the most potent greenhouse gases (CF_4 + C_2F_6 + CHF_3).

Table 6-3: PFAS testing results and Emission Factors for Municipal Waste-to-Energy combustion

Facility Test Report(s)	units		Björklund et al., (2023, 2024)	Strandberg et al. (2025)		Wohter et al. (2025); Wohter, Holfelder, et al. (2026); Wohter, Quicker, et al. (2026)		Wohter et al. (2025); Wohter, Holfelder, et al. (2026); Wohter, Quicker, et al. (2026)
Facility			Umea Energi	IVL Plant A		GKS		GKS
Location			Umea, Sweden, EU	Sweden, EU		Schweinfurt, Germany, EU		Schweinfurt, Germany, EU
Scale			Industrial	Industrial		Industrial		Industrial
Technology type			Moving grate	Moving grate		Moving grate		Moving grate
Furnace temperature	°C		up to 1100	1125		up to 1200		up to 1200
Combustion exhaust gas cooling	---		boiler + quench tower	boiler		boiler		boiler
Acid gas removal	---		wet scrubber: slaked lime	not reported		not reported		not reported
Stack CO_2 (dry basis)	%	≥	9	not reported		11% (estimated)		11% (estimated)
Testing Condition	---		routine operation	routine operation		reference case (baseline)		spiked with fluoropolymer + other*
Average fluoropolymer concentration in EU MSW	g/t		51	51		51		not applicable
Waste feed rate to furnace	t/hr		20	20		8		not applicable
Fluoropolymer (FP) mass input rate	kg/hr		1	0.5 (feed = 50% MSW)		0.4		8.4
Stack test method for water-soluble PFAS	---		modified EN 1948:1	OTM-45 | EN 1948:1		adapted OTM-45		adapted OTM-45
No. of water-soluble PFAS measured in stack	---		18	54		22		22
Stack total water-soluble PFAS	ng/Nm^3		4.6	0.33 | 0.52		0.25		0.4
Stack total water-soluble PFAS	g/hr		5.13E-04	3.3E-05** | 5.2E-05**		1.0E-05**		1.6E-05**
Stack PFAS levels influenced by scrubber water supply			not assessed	not assessed		Yes		Yes
Emission factor, g water-soluble PFAS/tonne fluoropolymer incinerated			0.50	0.065 | 0.10		0.025		1.9E-03
Stack CF_4 via OTM-50	µg/m^3		not measured	0	<	5.5***		700
Stack C_2F_6 via OTM-50	µg/m^3		not measured	0	<	0.55***	<	0.55***
Stack CHF_3 via OTM-50	µg/m^3		not measured	0	<	1.3***	<	1.3***
Other stack volatile F compounds via OTM-50	µg/m^3		not measured	79****		not detected		not detected
Main other stack volatile F compounds detected			not applicable	chlorofluorocarbons****		not detected		not detected
CF_4 + C_2F_6 + CHF_3 Climate Impact (as CO_2e)	µg/m^3		not applicable	not applicable	<	6.64E+04		5.17E+06
Climate Impact$_{CO2}$ / Climate Impact$_{CF4+C2F6+CHF3}$			not applicable	not applicable	≥	3253		37

*** other: AFFF concentrate + side-chain fluorinated polymer + perfluoropolyether**

**** Calculated using 5000 Nm^3 flue gas/tonne waste feed based on Hulgaard and Vehlow, 2010.**

***** Using commercial lab OTM-50 detection limits (DLs) reported by Troxler et al. 2025 for non-detect values to calculate Climate Impact because OTM-50 DLs not provided by Wohter.**

****** "Both compounds [HCFC-22 + CFC-11] were also present in field and laboratory blanks, generally within the same order of magnitude as stack concentrations." (Strandberg et al., 2025)**

6.5.2.1 Emissions of water-soluble PFAS

The emission factor shows how much water-soluble PFAS is formed and emitted for each tonne of fluoropolymer incinerated. This allows to evaluate the significance of the emissions and to compare the test cases on a consistent basis. Emission factors for water-soluble PFAS emissions from each of the above mentioned WTE plant were computed in three steps.

In a first step, a conservative estimate for the concentration of fluoropolymer in the MSW input was calculated for the first three columns of Table 6-3 where the plant feed was not intentionally spiked with fluoropolymer. The estimate is made using the 2020 EU27 + 3 annual mass flow of fluoropolymer to municipal WTE plants in Figure 4-1 (5.15 kt/year) and the Europe-wide 2020 annual quantity of MSW treated in municipal WTE plants (101Mt/year) from the Confederation of European Waste to Energy Plants (CEWEP) (https://www.cewep.eu/wp-content/uploads/2023/01/EU-Map-2020.pdf). The resulting estimate for the average concentration of fluoropolymer in European MSW feed to municipal WTE plants is 51 g/t (= 5.15 kt fluoropolymer ÷ 101Mt MSW. For the first three columns in Table 6-1, this estimated concentration is combined with the MSW feed rate to estimate fluoropolymer mass input rate. For the fourth column, the fluoropolymer spiking rate is used directly as the fluoropolymer mass input rate even though doing so does not account for the 51 g fluoropolymer/t MSW expected in the MSW that was co-fed with the spiking materials. This omission is conservative in that it results in overestimating the water-soluble PFAS emission factor for the case in the fourth column of Table 6-3. It is important to note that 51 g fluoropolymer/t MSW is used herein as the average concentration of fluoropolymer in MSW rather than as the average organofluorine concentration in MSW. Organofluorine materials other than fluoropolymers expected in the MSW feed to European municipal WTE plants include unused or expired medicines (Caron, 2020; OECD, 2022) as well as side-chain fluorinated polymers (SCFPs) applied to paper and textiles (Yamamoto, 2017).

In a next step, mass emission rates for total water-soluble PFAS for the four test cases (across three plants) are compiled in Table 6-3 and discussed in this paragraph. Where only stack gas concentrations were reported, 5000 Nm^3 flue gas/tonne waste feed was used to convert concentration to mass emission rate. This factor is based on basic waste combustion calculations presented by Hulgaard and Vehlow (2010). Regardless of feed spiking, stack total water-soluble PFAS was very low with stack concentrations ranging from 0.25 to 4.6 ng/Nm^3 with testing by Björklund at the high end of the range. Two short-chain perfluoroalkyl carboxylic acids (PFBA and PFHxA) made up most of the 4.6 ng/Nm^3 (Björklund et al., 2024). Similarly, perfluoroalkyl carboxylic acids accounted for over 40% of the total water-soluble PFAS at Plant A (Strandberg et al., 2025). At GKS where AFFF concentrate was handled and in one test case spiked into the MSW input (Wohter, Quicker, et al., 2026), PFBA and PFHxA were present in stack gas but overshadowed by emission of perfluoroalkyl sulfonic acids associated with AFFF concentrate. Strandberg et al. (2025) note that their single-run sampling approach may not adequately characterise the stack gas at Plant A and that they did not collect a sampling train field blank as part of testing this stack. Hence, it is not possible to determine the impact of potential external contamination on the results for Plant A. Results presented by Wohter, Quicker et al. (2026) demonstrated that reference (baseline) stack gas concentrations were high in the same two PFAS compounds (8:2 fluorotelomer sulfonate and HFPO-DA) as the corresponding field blank (not inserted in the stack). Based on the composition of AFFF concentrate and the process used to manufacture the fluorinated surfactants therein (Pabon & Corpart, 2002), the 8:2 fluorotelomer sulfonate appears related to handling AFFF concentrate in the field or in the analytical laboratory. As discussed in section 5.5.2.1, the elevated HFPO-DA levels in stack samples and in blanks observed by Troxler et al. (2025) were attributed to contaminated stack sampling train components (Shields, 2025). Where assessed, stack PFAS levels were found to have been influenced by PFAS in the scrubber supply water. HFPO-DA is not expected in WTE plant stack gas because it is unlikely to survive temperatures above 480°C (Blotevogel et al., 2023).

In the third and final step to compute the emission factor (g water-soluble PFAS/tonne fluoropolymer incinerated), the tabulated total water-soluble PFAS mass emission rates are divided by the

corresponding fluoropolymer mass input rate in Table 6-3; see step 1 above. As Table 6-3 shows, the highest water-soluble PFAS emission rate (5.12E-04 g/hr) and thereby the highest emission factor (0.5 g water-soluble PFAS/tonne fluoropolymer incinerated) corresponds to work by Björklund et al. (2023). This high-end emission factor is comparable to the emission factors for full-scale hazardous waste incinerators presented in Table 5-1. Using the logic presented at the end of section 5.5.2.1, an emission factor of this magnitude is less than the emission factor one would calculate when 99.9999% destruction had been demonstrated for a given compound.

In addition to the water-soluble PFAS routinely analysed in OTM-45 stack gas samples, Wohter et al. (Wohter, Holfelder, et al., 2026; Wohter, Quicker, et al., 2026) also present TFA results at different points in the GKS system. They note that TFA was detected in the final stack gas but not in the raw gas entering the air pollution control system. Furthermore, they show that TFA stack gas outlet mass flows (corresponding to a 5 - 21 ng/Nm^3 stack concentration range across different test cases) result from TFA in the process water supply to wet scrubbing.

6.5.2.2 Emissions of volatile fluorinated compounds

Available information on stack concentrations of volatile fluorinated compounds (via OTM-50) is compiled in Table 6-3. Consistent with IVL's discussion of OTM-50 results for Plant A (Strandberg et al., 2025), high levels of HFP (C_3F_6) seen at similar concentrations in both the stack samples and the field blank were not included in the volatile fluorinated compound concentration values in Table 6-3. There is no plausible route to HFP formation under the furnace conditions reported for Plant A. Except for chlorofluorocarbons at Plant A (second column) and CF_4 at GKS during excessive organofluorine spiking, the volatile fluorinated compound emission concentrations are generally reported as not detected. As with the OTM-50 results for the Veolia Port Arthur hazardous waste incinerator (see chapter 5.5.2.2), the two chlorofluorocarbons (HCFC-22 and CFC-11) detected at Plant A are common refrigerants found in the analytical laboratory. As Strandberg et al. (2025) stated, "both compounds were also present in field and laboratory blanks, generally within the same order of magnitude as stack concentrations." Consequently, the chlorofluorocarbon emission concentration in the second column of Table 6-3 is understood to be a laboratory artifact not representative of actual stack emissions. The CF_4 concentration in the fourth column is discussed below in the last paragraph of chapter 6.5.2.2. In addition to integral sampling via OTM-50, Wohter et al. (Wohter et al., 2025; Wohter, Quicker, et al., 2026) continuously monitored GKS stack gas for CF_4 via Fourier Transform Infrared (FTIR) spectroscopy.

The table also compares the Climate Impact (see equation 5-8) of three of the most potent greenhouse gases (CF_4, C_2F_6, and CHF_3) as CO_2e to the facility's CO_2 stack concentration. To enable this comparison for the third and fourth columns, a CO_2 concentration of 11% on a dry basis was used as a representative value for municipal waste-to-energy flue gas at stack conditions, consistent with typical values reported for MSW incineration flue gas in the literature (e.g. (Christensen, 2011)) and from proprietary data on excess air levels and CO_2 concentrations from more than 100 WtE-facilities which Ramboll have assisted in relation to WtE operating assistance, construction or upgrade.

Additionally, Wohter et al. (Wohter et al., 2025; Wohter, Holfelder, et al., 2026; Wohter, Quicker, et al., 2026) reported use of OTM-50 without providing information on corresponding detection limits. Hence, commercial laboratory OTM-50 detection limits reported by Troxler et al. (2025) were used for non-detected volatile fluorinated compounds. Testing results in the first three columns of Table 6-3 were collected under routine operation without feed spiking. Under these conditions, the Climate Impact of $CF_4 + C_2F_6 + CHF_3$ (conservatively assuming presence at detection limits) from the GKS municipal WTE plant would be a factor of 3253 times less than the Climate Impact of this plant's CO_2 emission.

The results in the fourth (right-most) column of Table 6-3 correspond to GKS plant operation co-feeding MSW and very high quantities of fluoropolymers and other organofluorine materials. The fluoropolymer spiking rate alone (8.4 kg/hour or 1.05 kg fluoropolymer/tonne MSW) is equivalent

to a fluoropolymer concentration in MSW input 21 times higher than the conservative estimate computed in the first step in chapter 6.5.2.1. However, spiking the other organofluorine materials appears to had a stronger influence on volatile fluorinated organic emissions. These other materials were intermittently-fed 1 litre plastic bottles of liquid AFFF concentrate, intermittently-fed small plastic canisters of perfluoropolyether, and continuously-pumped SCFP "coating suspension"– for a total spiking organofluorine rate of 12 kg/hour (= 8 t MSW/hr × 0.15%) (Wohter et al., 2025; Wohter, Quicker, et al., 2026). Both AFFF concentrate and SCFP suspension are fluorotelomer-based products (Glüge et al., 2020). This is important because Yamada et al. (2017) have shown that $\cdot CF_3$ is a major product of fluorotelomer combustion under conditions representative of the waste bed along the grate of municipal WTE plants. Under routine WTE furnace operating conditions, equations 5-6 and 5-7 shows that $\cdot CF_3$ free radicals would react with abundant H· atoms and O· atoms to yield HF via the reactions in equations 5-2 and 5-3. However, the testing summarised in the fourth column was conducted far from normal conditions. In addition to its fluorotelomer content, AFFF concentrate contains a large fraction of medium-chain (C8 – C10) hydrocarbon surfactants (Pabon & Corpart, 2002). Kennedy et al. (2025) emphasise that it is not possible to prevent fluorocarbon formation without H· atoms and O· atoms. Therefore, when combustion of AFFF concentrate containers intermittently consumed locally available oxygen and hydrogen atoms, episodes of CF_4 formation occurred. The FTIR display of transient CF_4 emission peaks shown by Wohter et al. (Wohter et al., 2025; Wohter, Quicker, et al., 2026) show a pattern of CF_4 emissions associated with feeding containers of liquids with elevated hydrocarbon content. Even under these extreme conditions unrepresentative of typical municipal WTE plant operation, the Climate Impact of CF_4 + C_2F_6 +CHF_3 is a factor of 37 times less than the Climate Impact of this plant's CO_2 emission.

6.5.3 Broader implications

The emission factors estimated in chapter 6.5 are based on testing at only a few of the approximately 500 municipal WTE plants in Europe. Nevertheless, each of the relevant test sites employed moving grate combustion in use at plants accounting for over 92% of the European municipal WTE design capacity as shown in Table 6-1. Therefore, these emission factors are considered applicable to and representative of municipal WTE combustion general practice in Europe. If additional full-scale stack testing is planned in order to reduce uncertainty about PFAS emissions, it would be productive to focus on fluidised bed plants to confirm results comparable to moving grate plants. As part of the national initiative to analyse PFAS emissions to air from a wide range of incineration facilities in France (Volcovschi, 2025), new fluidised bed WTE plant emission data will be generated. Although fluidised bed plants operate lower temperatures, they are expected to achieve comparably low PFAS emission factors due to efficient combustion via uniform mixing and heat transfer (see chapter 6.3).

Full-scale testing results presented herein support the conclusion reached previously by researchers at the National Institute for Public Health and the Environment in the Netherlands (RIVM) (Bakker et al., 2021) that if the minimum operating conditions required under the Industrial Emissions Directive (see chapter 6.1) are met, waste incineration is not expected to generate PFAS emissions other than CF_4 and C_2F_6 as likely PICs. Testing at GKS further indicates that elevated CF_4 formation was observed only under non-routine test conditions involving strong spiking with $\cdot CF_3$ containing sources together with elevated hydrocarbon content (i.e., AFFF concentrate in containers). The conclusion from RIVM's comprehensive review of the relevant literature is important for at least three reasons:

- CF_4 and C_2F_6 do not fit the toxicity profile generally associated with PFAS, because they are highly stable (Droste et al., 2020), poorly water-soluble gases (Park et al., 1982) rather than mobile, water-associated substances. In the EU REACH registrations[1],[2] CF_4 and C_2F_6

[1] https://chem.echa.europa.eu/100.000.815/dossier-view/322f3a93-cf8c-479f-9dc6-8c0dfb8c138b/0696d0bb-39f3-4b1f-9686-d4524ae41ad1_0696d0bb-39f3-4b1f-9686-d4524ae41ad1?searchText=200-896-521573

[2] Perfluoroethane 100.000.855 | Active REACH registrations - ECHA CHEM

are classified only as a pressurised gases (H280), there is no harmonised classification according to CLP.

- In municipal WTE plants, it is likely that MSW provides low concentrations of pre-cursors and sufficient hydrogen sources to suppress formation of CF_4 and C_2F_6 during combustion of fluoropolymer pyrolysis gas under routine operating conditions; see chapter 6.5.1.
- CF_4 and C_2F_6 are already regulated as greenhouse gas emissions. In a scenario where a municipal WTE plant were to intermittently feed liquid containers with concentrated $\cdot CF_3$ sources and elevated hydrocarbon content into the furnace, the plant would be required to report CF_4 emissions to the competent authority if relevant thresholds are exceeded. The European Pollutant Release and Transfer Register (PRTR) Regulation (The European Parliament and the Council of the European Union, 2006) requires municipal WTE plants to annually report emissions of perfluorocarbons (sum of CF_4, C_2F_6, C_3F_8, C_4F_{10}, c-C_4F_8, C_5F_{12}, and C_6F_{14}) if perfluorocarbon emissions reach the 100 kg/year reporting threshold.

With regard to climate policy instruments, municipal WTE plants are currently subject to reporting obligations for greenhouse gas emissions under EU law, and potential inclusion in the full EU Emissions Trading System for greenhouse gases from 2028 is under consideration but not yet fully implemented across all Member States. This is subject to a Commission feasibility assessment in 2026 and potential Member State opt-outs until 2030.

7. Landfilling

While in the previous chapters the main EoL routes for fluoropolymers have been addressed, the following chapter concentrates on conditions of safe disposal (e.g. long-term safety) of fluoropolymers at landfills. To re-emphasise earlier findings of this report:

- In 2020, around 23.5 kt of fluoropolymer waste were collected via different residential as well as commercial and industrial waste streams, and around 13% or 3.09 kt of the collected fluoropolymer waste from different sources was landfilled (Conversio Market & Strategy, 2023).
- Fluoropolymers are at present particularly landfilled from residential waste as well as from waste stemming from electronics, ELVs including automotive shredder residues and specific commercial and industrial waste (see chapter 3).

Key messages

- Only a small fraction of fluoropolymer waste is disposed of in landfills. This share is expected to decline further as EU policy discourages landfilling and encourages instead recovery or other treatment activities.
- When fluoropolymer waste is disposed of in landfills, it can be diverted to various classes of the landfills based on the waste stream. Residential and private waste streams contribute a small proportion compared to commercial and industrial waste.
- It is expected that most of the fluoropolymer waste is being sent to landfills for non-hazardous waste, fulfilling the testing criteria due to their properties. Alternatively, fluoropolymer waste ends up in landfills for hazardous waste.
- Emissions are the biggest concern of disposal. Leachate is a dominant pathway, with air releases being considered for lesser contribution.
- The scientific literature is not consistent relating to the question if fluoropolymers can degrade to or generate substances of concern in leachate.
- Some few studies suggest them as potential source of leachate contamination with short-chain PFASs like TFA, PFPrA, and PFOA (Meng et al., 2024).
- Fluoropolymers, have high molecular weight, low water solubility and strong C–F bonds, resulting in very low mobility and high chemical, thermal, hydrolytic and photochemical stability, with no meaningful degradation under normal environmental or landfill-relevant conditions (Henry et al., 2018; Henry & Timmer, 2025).
- Closer evaluation has recently been provided by a study that demonstrates that discharge of PTFE particles into the environment would not lead to environmental release of non-polymer PFAS (Henry & Timmer, 2025).
- A significant proportion of PFAS may derive from non-polymeric PFAS and other non-fluoropolymer constituents in the waste (Joudan et al., 2024).
- Currently, the respective proportion of PFAS in leachate that is directly derived from fluoropolymer waste is not known. More research is needed to better understand the mechanism of release and the contribution of fluoropolymer to PFAS release.
- Landfilling of waste in the EU is regulated by a very prescriptive legislative context mostly embodied in the Landfill Directive and the Waste Acceptance Criteria Decision. These regulations create a multi-barrier system: for pretreatment of the mixed waste, acceptance criteria for the various classes of landfills, permitting and operational requirements, and monitoring coupled with long-term aftercare.
- In addition, technologies exist to treat leachate and thus decrease PFAS concentrations. Although such technologies are progressing, their performance is still mixed. Considering that leachate is a complicated matrix, the capability of efficient treatment, convenience of full-scale application, and cost needs to be considered carefully when selecting the optimal treatment methods.

Most fluoropolymer waste comes from industrial sources such as chemical and pharmaceutical companies, food and beverage production, the semiconductor industry, and energy sectors. Professional companies typically manage this waste, and some fraction may end up landfilled. fluoropolymer applications from electronics and semiconductors are collected in electronic waste and landfilled when not recycled. fluoropolymer used in automotive applications often ends up as part of auto-shredder residue, which is partially landfilled. A small fraction of fluoropolymer waste is collected in mixed household and municipal waste streams, related to cookware, apparel and other consumer items and smaller consumer electronics, which also might end up landfilled.

In line with Article 6 of the Landfill Directive as interpreted by the Court of Justice of the European Union, fluoropolymer waste should generally not be accepted at landfills because it is a recoverable material whose landfilling is incompatible with the waste hierarchy and the Directive's objective to reduce the disposal of untreated waste. Its calorific value and recyclability make fluoropolymer waste suitable for material recovery or energy recovery processes, and their diversion from landfill contributes to the minimisation of residual waste volumes.

However, it is assumed that landfilling takes place to a small extent. This apparent contradiction between policy intent and waste management practice can be explained by a combination of technical, economic, and regulatory factors which are elaborated in chapter 4.3. fluoropolymer waste entering landfills also rarely appears as a clean stream, instead, it is mixed with municipal solid waste, electronic waste, or automotive shredder residue. Extracting and isolating it from these heterogeneous mixtures is technically challenging and considered uneconomic. Because most fluoropolymer waste is not classified as hazardous, it can legally be disposed of in non-hazardous landfills after pre-treatment. Economic factors reinforce this outcome - landfilling is often cheaper and more accessible than specialised incineration or recycling. As a result, despite the EU's goal of phasing out landfilling of municipal waste, a small amount of fluoropolymer waste still follows this route. Several responses to the value chain survey indicated geographical differences as regards to landfilling possibilities.

While a certain part of fluoropolymer waste still ends up on landfills it is important to understand that in the EU strict measures are in place for ensuring that landfills manage waste in a way that environmental impacts are controlled.

In practice, safe disposal of fluoropolymers in landfills relies on three pillars. First, application of the existing EU waste hierarchy ensures that landfilling is used only as a last resort, thereby reducing the overall mass of fluoropolymer waste deposited. Second, strict adherence to the landfill acceptance procedures, including basic characterisation, leaching tests, and verification at the gate, ensures that wastes are directed to the correct landfill class and that they comply with waste acceptance criteria. Finally, reliance on engineered containment - through geological barriers, low-permeability liners, leachate collection and treatment, and long-term monitoring - provides control measures that so even persistent materials do not pose unacceptable risks to soil and groundwater.

7.1 Relevant EU legal provisions for landfills

The environmental protection approach embodied in the EU legislation on landfills relates to various aspects that are important in the context of the landfilling of fluoropolymer waste. The legal framework on landfills contains criteria to mitigate environmental risks from the operation of landfills, with a specific view on impacts for risks for soil and groundwater, which are:

(1) General discouraging of landfilling as treatment method

Landfilling is defined as a method of disposal and thus ranks lowest in the EU waste hierarchy. The EU has committed the Member States to (i) endeavour to ensure that as of 2030, all waste suitable for recycling or other recovery, in particular in municipal waste – one important source of fluoropolymer waste sent to landfills – shall not be accepted in a landfill with the exception of waste for which landfilling delivers the best environmental outcome and to (ii) take the necessary measures

to ensure that by 2035 the amount of municipal waste landfilled is reduced to 10 % or less of the total amount of municipal waste generated (by weight).

(2) Introduction of a system of landfill classes with different requirements for different types of waste

According to the Landfill Directive 1999/31/EC, landfills are categorised into three types, each with specific criteria for acceptable wastes and different technical requirements for establishment, permitting and operation in order to control emissions:

- Landfill for inert waste: only inert waste is to be disposed of at these landfills. In return, the technical requirements are rather limited;
- Landfill for non-hazardous waste: these landfills may be used for municipal waste, non-hazardous waste of any other origin, and stable, non-reactive hazardous wastes. The technical requirements are medium
- Landfill for hazardous waste: hazardous waste may be accepted at these landfills but there are still criteria for acceptance so that not all wastes may be accepted. The technical requirements are strict

In addition, underground storage is considered a special form of hazardous waste disposal.

(3) Permitting requirements and siting criteria

Every landfill needs an environmental permit stipulating criteria of the site, wastes to be accepted, operations, monitoring and control procedures mirroring these legal requirements.

(4) Requirement for pre-treatment of (mixed) waste

Key feature of the Landfill Directive is the requirement of what waste will be eligible to be accepted at (the different classes of) landfills. For all classes of landfills, an important rule is that only waste must be landfilled that has been subject to treatment (Article 6 (a) Landfill Directive). In the *Malagrotta* ruling (Case C-323/13, 15 October 2014), the Court of Justice of the European Union held that "treatment" must be understood as a physical, thermal, chemical or biological process, including sorting, which materially changes the characteristics of the waste to reduce its volume, hazardous nature, or environmental impact, and to facilitate its handling or enhance recovery and that mere sorting or transfer without substantive alteration of the waste would not satisfy the Directive's requirements. The judgment emphasised that the treatment must effectively separate recoverable fractions, in line with the waste hierarchy, and that landfilling of untreated or inadequately treated mixed municipal waste would constitute a breach of EU law.

(5) Harmonised acceptance criteria for waste at the different classes of landfills

In the context of acceptance of waste at landfills, the Landfill Directive sets out that only certain pre-defined types of waste must be accepted at landfills. Commission Decision 2003/33/EC ("EU Waste Acceptance Criteria (WAC) Decision") operationalises these requirements with binding effect for the Member States by defining uniform criteria and testing procedures for the acceptance of different types of waste at the types of landfills recognised by the Landfill Directive, i.e. landfills for inert, non-hazardous, and hazardous waste classes. These criteria are mainly based on waste characterisation, leaching behaviour, and total pollutant content, with the objective of ensuring that the composition and environmental emissions of landfilled waste remain specifically for each landfill class within thresholds compatible with the protection objectives of the Directive.

(6) Monitoring and after-care

Landfill operators should have systems in place for monitoring and aftercare once a landfill is closed to avoid long-term environmental risks or keep them to a minimum. After closure, responsibilities will continue for:

- The control of leachate production and composition,
- Collecting and treating leachate,

- Monitoring groundwater quality, surface water, and landfill gas emissions.

The relevant authority determines the duration of these responsibilities. All measures should be taken to ensure that parameters, frequency, and analytical processes are, as far as possible, in line with harmonised norms to identify possible pollution or structural faults.

The operator remains responsible for:

- The maintenance of containment systems,
- The continued integrity of the geological barrier and cover,
- Intervening if monitoring results show that limit values have been exceeded.

The legal framework on landfills itself contains various dimensions of protecting the environment from emissions generated by landfills. For the discussion how a safe disposal of fluoropolymer waste can be ensured, we understand the following dimensions are most relevant and will be discussed below:

- Requirement for pre-treatment of (mixed) waste in order to be accepted at landfills
- Criteria and requirements for acceptance of waste at different landfill classes
- Operation / permitting requirements
- Monitoring and after-care

However, it should be noted that the general discouragement of landfilling as a treatment option in the EU contributes to reducing the overall volume of waste directed to landfills. By favouring options higher up the waste hierarchy for managing wastes other than disposal in landfills, reliance on the disposal to landfills approach is reduced, subsequently decreasing the potential of impacts for long-term containment. Strict siting regulations also add another level of safety. This includes the necessity of a natural geological barrier and/or engineered sealing systems. In practice, this limits the transport of any contaminants from the landfill body into surrounding soil and groundwater, thereby enhancing environmental safety.

Details on safe conditions are further provided in Appendix 3 – Expanding fluoropolymer landfilling.

7.2 Environmental fate of fluoropolymers in landfills

While in the previous sections the general provisions legally required and in place in the EU for landfills were elaborated, showing that in principle safe conditions are in place, one aspect that is often the centre of discussion is to what extent fluoropolymers can enter the environment following landfilling. This section summarises main findings from the available literature, focusing first on considerations related to stability and subsequently on two main emission pathways that may occur once fluoropolymer waste enters landfills: potential releases to landfill leachate and emissions to air. It should be noted, however, that the available literature is limited and does not include systematic evaluations of fluoropolymer biodegradation under representative landfill conditions.

7.2.1 Stability of fluoropolymers

Polymeric PFAS, including fluoropolymers, are characterised by high molecular weight, low water solubility and the presence of strong carbon–fluorine bonds. These intrinsic properties limit mobility and confer a high degree of chemical and physical stability, resulting in resistance to degradation under use conditions (Améduri & Hori, 2023), nevertheless data referring to typical environmental conditions and therefore stability in the dense of resistance to degradation are limited. Some sources consider fluoropolymers as highly resistant to environmental degradation, and there is limited evidence to suggest that they break down to form low molecular weight PFAS under ambient conditions (Henry et al., 2018). When assessing stability under landfill conditions, particular consideration is required with respect to biodegradation, as microbial processes represent a key transformation pathway for many organic PFAS but appear to play a negligible role for fluoropolymers. Available evidence indicates that fluoropolymers do not undergo biodegradation

under aerobic or anaerobic conditions in soil, water, sediment or activated sludge systems (Henry et al., 2018; Henry & Timmer, 2025). Photochemical degradation of fluoropolymers is not expected to occur, and experimental data indicate resistance to photolysis (Henry et al., 2018; Henry & Timmer, 2025). Fluoropolymers are also thermodynamically stable under normal environmental conditions and exhibit high thermal stability, with decomposition reported only at temperatures far exceeding those encountered in landfill or atmospheric environments (Ellis et al., 2001; Henry & Timmer, 2025). In addition, they are hydrolytically stable and not subject to hydrolysis-catalysed degradation (Henry et al., 2018). Recent laboratory studies investigating degradation under extreme or artificial conditions provide mechanistic insights but cannot readily be transferred to real-world landfill environments (Joudan et al., 2024). The available evidence indicates that fluoropolymers with fully fluorinated carbon backbones are unlikely to undergo significant degradation under landfill conditions or to act as a direct source of low molecular weight PFAS in landfill leachate. Uncertainties remain however due to limited long-term field data.

7.2.2 Landfill leachate

Lohmann et al. (2020), referencing (He et al., 2019; Praagh et al., 2019), discuss landfills as potential sources of plastic and microplastic release and more broadly note their possible contribution to PFAS occurrence in landfill leachate. However, a closer examination of the original sources does document inputs related to microplastics, these studies do not provide evidence that landfill leachate can be contaminated with PFAS due to fluoropolymer presence. The authors indicate that despite the exceptional chemical and thermal stability of fluoropolymers, particles are subject to disintegration into microplastics through weathering and physical stress, which facilities further dispersion and increased bioavailability (Lohmann et al., 2020). Importantly, the cited discussion does not specifically address the release of PFAS from such fluoropolymer-derived particles. In this context, Praagh et al. (2019), in a study funded by the Nordic Council of Ministers, questioned whether landfills are a major contributor to microplastic pollution, emphasising the large variability observed in microplastic counts and polymer types across landfill leachates. That study concluded that, overall microplastic loads from landfills appear small relative to other sources such as wastewater effluents and untreated and treated sludge (Praagh et al., 2019).

With respect to the potential contamination of leachate with non-polymeric PFAS from fluoropolymer products, a recent study in China conducted leaching experiments in simulated solutions, including one designed to mimic landfill leachate (pH = 2.64 ± 0.05[3]) and showed PFOA leaching rates of 34 ± 43%. As test materials 10 different samples, that mainly consisted of different PTFE materials from China as well as one PVDF sample were used. Based on these results, the authors concluded that fluoropolymer disposal in landfills and open storage poses a non-negligible risk of PFAS release to the environment and called for precautionary measures to minimise such emissions (Meng et al., 2024). Further, Joudan et al. (2024) showed that fluoropolymer and non-fluoropolymer tubing can leach short-chain PFAS into water under controlled laboratory extraction conditions,, with fluoropolymers generally releasing higher concentrations. The PFAS profiles varied by polymer type and even between samples of the same material, likely due to manufacturing differences or contamination during handling. Ultrashort-chain PFAS, particularly trifluoroacetic acid (TFA) and perfluoropropanoic acid (PFPrA), dominated over longer-chain PFCAs across all materials tested, including nonfluorinated polymers. The study was conducted using simplified aqueous extractions and did not attempt to simulate environmental conditions. Therefore, factors relevant to real-world systems such as ageing, degradation, or complex geochemical conditions were not assessed. Despite this, the findings demonstrate that PFAS release is not limited to fluoropolymers and highlight substantial variability linked to material production and history. This variability is particularly relevant for heterogeneous waste streams, where diverse polymer materials may act as PFAS sources (Joudan et al., 2024).

[3] according to Chinese leaching test HJ/T 300-2007, Solid Waste−Extraction procedure for leaching toxicity−Acetic acid buffer solution method

A recent article by Henry & Timmer (2025) presents results of intensive investigations to clarify the question whether PTFE fine powder (meeting ASTM D4895-18 standards) would degrade to and subsequently release substances of concern if found in the environment. While in this study ultrashort PFCAs were not considered, the results of various scientifically accepted tests related to environmental fate and behaviour test methods showed that the tested PTFE fine powder does not contribute to elevated PFAS concentrations in wastewater treatment plant discharges or solids. It is also not an inhibitor to sludge microbes. It is expected that these results are also valid for potential landfill leachate. The authors also conclude that available data indicate that the tested PTFE fine powder is very unlikely to significantly distribute between environmental media or be taken up and stored by plants, due to its very low volatility and solubility and its limited tendency to adsorb to soil (Henry & Timmer, 2025).

The scientific literature is not consistent relating to the question if fluoropolymers can degrade to or generate substances of concern in leachate. Non-polymeric PFAS content in landfill leachate can result from waste containing non polymeric PFAS or even from other polymers as shown by (Joudan et al., 2024) under laboratory conditions, and is not necessarily derived from fluoropolymers.

Therefore, regardless of the source landfill leachate treatment in any case needs to manage non-polymeric PFAS contamination. To minimise environmental risks, including the direct discharge of PFAS into surrounding soil and water systems, regular maintenance of leachate collection systems is essential. A recent review by Sabba et al. (2025), provides a summary of existing PFAS treatment technologies and evaluates their suitability for leachate (see Figure 7-1). These technologies were assessed based on several criteria, including effectiveness in PFAS removal, technological readiness, and economic considerations. Capital expenditure (CAPEX) and operational expenditure (OPEX) were ranked from low to high, providing a cost perspective for implementation, while technological readiness was scored on a scale of 1 to 5, with 5 representing the most developed method. These ratings were based on manufacturer data and peer-reviewed PFAS studies. Non-quantitative factors, such as technological readiness, are assessed relative to each other (Sabba et al., 2025).

As seen in the figure below, most of the available treatment methods currently show low levels of technological readiness, highlighting a gap between research-scale testing and full-scale implementation. This means that no single technology is currently capable of efficiently and cost-effectively removing PFAS from landfill leachate under real conditions. As a result, a combination of treatment strategies may be employed. For example, a two-step approach could be considered: 1) a pretreatment step designed to reduce leachate volume and PFAS concentration through concentration or separation technologies (e.g., membrane filtration, adsorption, foam fractionation), followed by 2) a destructive method such as high-temperature incineration or advanced oxidation to permanently degrade PFAS compounds.

Initiatives are ongoing to identify, test and pilot the most effective, technically feasible & economically viable technologies for the destruction of short-chained PFAS commonly found in process water (Global Impact Coalition, 2025). Results thereof, will most likely be useful for the aspect of treating landfill leachate as well.

Emissions to air

Multiple studies have reported the presence of PFAS in landfill gas, indicating that landfills can release these substances into the atmosphere. PFAS concentration increases have also been measured downwind of both landfills and wastewater treatment plants. However, studies investigating the specific contribution of fluoropolymers to such emission are not available.

One of the earlier studies, from Ahrens et al. (2011), examined whether WWTP and landfills release PFAS into the atmosphere. Passive air samples placed in and around one WWTP and two landfill sites in Canada showed that PFAS concentrations in air were substantially higher than at background locations. At the WWTP, concentrations for the sum of polyfluoroalkyl compounds were 3-15 times higher, while at landfills they were 5-30 times higher (Ahrens et al., 2011). This study did not differentiate between fluoropolymers and other potential sources.

Similarly, Lin et al. (2022) reported that PFAS detected in air samples around waste management infrastructure were primarily PFAS precursors and their semi volatile transformation intermediates (e.g., sec-FOTHs). The study estimated daily PFAS emission of approximately 95.8 mg/d, suggesting that landfills could be significant source of atmospheric PFAS compared to WWTPs (Lin et al., 2022). This study did not differentiate between fluoropolymers and other potential sources.

In contrast, Wahlström et al. concluded that emissions of PFAS to air from landfills in Europe may be limited, given that closed sites are typically sealed. The study also referred to field studies in Ireland and Germany where they found no significant increases of ionic PFAS in surrounding air. However, volatile precursors such as fluorotelomer alcohols were detected at levels 1.5 – 3 times higher than near landfills compared to background (Wahlström et al., 2021). This study did not differentiate between fluoropolymers and other potential sources.

Technology	GAC	IX	RO	Foam Fract.	EO	SCWO	HALT	Plasma
Type	Separation	Separation	Separation	Concentration	Degradation	Degradation	Degradation	Degradation
CAPEX ($-$$$$)	$$	$$	$$$$	$$	$$$	$$$$	$$$$	$$$$
OPEX ($-$$$$)	$$$	$$$	$$$$	$	$$	$$$	$$	$$$
Applicability for Landfill Leachate[a]	1	2	3	5	4	4	4	5
Level of Technological Readiness	5	5	5	2	3	2	1	1
Energy Consumption	5	5	3	4	3	1	2	1
Chemical Addition	5	5	5	4	1	2	2	3
Treatment Capacity	5	5	4	4	3	2	2	1
Long-chain PFAS Removal	4	5	5	5	5	5	4	5
Short-chain PFAS Removal	1	5	5	1	2	5	4	1
Gas Emissions	5	5	5	5	3	1	2	2
Aqueous Byproducts	5	5	4	5	3	3	4	3

[a]*Technological capability of different processes for PFAS treatment in complex landfill leachate matrices.*

Readiness Factor	Treatment Criteria
5	The technology is highly suitable for the category
4	The technology is appropriate
3	The technology is adequate with minor improvements
2	Greater attention is required
1	The issue defined in the category should be carefully addressed before implementation

GAC – granular activated carbon; IX – ion exchange; RO – reverse osmosis; EO – electrooxidation; SCWO – supercritical water oxidation; HALT - hydrothermal alkaline treatment; CAPEX – capital expenditure; OPEX – operational expenditure

Figure 7-1: Evaluation matrix of various PFAS treatment technologies (as provided in Sabba et al. 2025)

Overall, while some available studies indicate that landfills can release PFAS to air, the contributions to emissions stemming particularly from fluoropolymers have not been documented. In Europe, PFAS emissions overall are thought to be minor due to engineering controls at modern landfills, but

evidence suggests that precursor compounds, especially FTOH, may still be released. Importantly, identified studies do not distinguish the contribution of fluoropolymers to these emissions, leaving a critical knowledge gap.

Both leachate and atmospheric pathways are potentially relevant for landfills, but releases from fluoropolymers have not been quantified source of emissions. More research is needed to better understand the mechanism of release and the potential contribution of fluoropolymers to PFAS release.

8. Metal recycling

Fluoropolymers are widely applied, in layers, as coatings, or integrated parts in metal products (e.g., non-stick frying pans, coated pipes from the chemical industry, or fluoropolymer-coated facade elements). Therefore, 2.71kt (equals 11.5%) of the waste that contains fluoropolymer end up in the metal recycling stream. The following chapter explains capabilities in Europe and key processes involved.

Key messages

- Fluoropolymers are widely used as coatings, linings, or small parts in metal products like pipes, fittings, cables, and machinery. When these items reach the end of life, they usually go into normal metal recycling routes instead of separate fluoropolymer-specific streams.
- After collection and pre-processing such as dismantling, shredding or separation, metal fractions that contain fluoropolymers are sent to steel, aluminium or copper smelters.
- Mechanical pre-treatment like shredding, sorting, and granulation can remove some fluoropolymer plastics, for example, cable insulation, from metals. But many fluoropolymers are firmly attached coatings or small parts and cannot be taken off. In those cases, the material goes into high-temperature furnaces along with metal scrap.
- Typical furnace temperatures and flue-gas conditions in steel and non-ferrous metal recycling are designed to achieve complete oxidation of organic compounds in off-gases. It is expected that fluorine mostly ends up in slag or air pollution control residues instead of being released directly into the air.
- Steel and aluminium smelters are prepared to handle intentional fluorine inputs like fluorspar in steelmaking and aluminium fluoride in aluminium smelting. This means these furnaces are used to dealing with some fluorine in slag and gas cleaning systems.
- Emission reports for metal furnaces list HF and organic pollutants among the off-gas components. However, they do not clearly separate fluoropolymer contributions from other sources like fuels or fluxes. The exact impact of fluoropolymers on total fluorine emissions from metal recycling is still not well known.
- No evidence was found that typical levels of fluoropolymers in scrap negatively affect metal quality, as quality issues are mainly associated with metallic “tramp elements”.

For other metal products that contain fluoropolymers or are coated with fluoropolymers, the main phase for their release and destruction is after they reach end-of-life. If the major fraction of the product is metal, these are likely to enter one of the key metal recycling routes. After entering metal smelters, fluoropolymers are subjected to high processing temperatures, which are expected to destroy most organic constituents, including fluoropolymers. However, depending on the processing conditions, thermal decomposition may also result in the formation and potential release of fluoropolymer decomposition products, PFAS or other hazardous substances.

As future discussions on this aspect affect metal recycling plants, this chapter outlines relevant recycling facilities, their location, and subsequently their operating conditions. Particular attention is given to the following product groups, which are expected to contribute significantly to fluoropolymer content in recycling streams:

- Seals, gaskets, valve seats, and coated fittings used in infrastructure, buildings, and industrial applications
- Electronic components and waste electrical and electronic equipment (WEEE) containing fluoropolymers
- Cookware and household items
- Automotive and transport-related components

- High-performance industrial machinery and equipment

Once these products reach their end-of-life phase, they typically undergo the following steps:

1. Collection: End-of-life products are collected through their sector and/or product specific collection system.
2. Dismantling and pre-processing: After collection, waste is dismantled, manually or mechanically, to separate major material fractions. Pre-processing may include shredding, sorting, and removal of hazardous or valuable components. However, fluoropolymer-containing parts (e.g., coatings) may not be removed at this stage due to adhesive bonding or their presence in complex assemblies.
3. Smelting and refining: Separated metal fractions are transferred to advanced metallurgical facilities for smelting and refining. These processes usually involve high temperatures which cause most organic materials, including fluoropolymer, to be destroyed.

Further details are covered in the following sub-chapters.

8.1 Metal recycling in Europe

In identifying representative recycling plants, it is important to recognise the diversity of metals commonly used in household and industrial applications. Broadly, these can be classified into **ferrous metals**, which contain iron (such as steel and its alloys) **and non-ferrous metals**, such as aluminium, copper, lead, zinc, and others (see Figure 8-1).

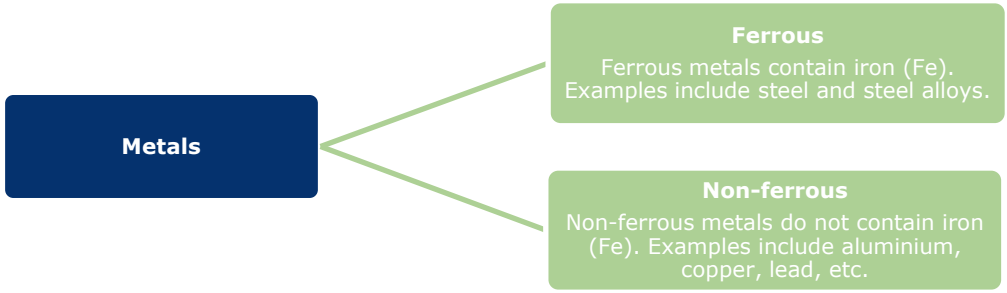


Figure 8-1: Two main groups of metals (based on (EuRIC, n.n.))

In the following three key metals are considered: ferrous metals/steel, and two non-ferrous metals, namely aluminium and copper.

8.1.1 Ferrous metal recycling

Ferrous metals, particularly steel, represent the backbone of Europe's metal recycling sector. This is clearly visible when considering the distribution and quantity of steel plants in Europe (see Figure 8-2). In the European steel industry, production is carried out through two main routes: the electric arc furnace (EAF) and the blast furnace and/or basic oxygen furnace (BF-BOF). The EAF route is primarily scrap-based and currently accounts for 39% of steel production. The BF-BOF route, in contrast, relies mostly on virgin iron ore but still incorporates some share of scrap. However, as can be seen from Figure 8-2, both processes are often located nearby or combined at one plant. Overall, more than half of all steel produced in Europe is made from recycled scrap, even though the majority of production capacity remains BF-BOF based (Eurofer, 2016). The bulk flows of raw materials feeding into these processes include scrap, iron ore, coking coal, alloying elements and coating materials (Eurofer, 2016). The processes of BF-BOF and EAF are described in more detail in the following sub-chapters.

Figure 8-2: Map of EU primary steel production sites - blast furnace and/or basic oxygen furnace (BF-BOF). Source: (Eurofer, 2020)

8.1.2 Nonferrous metal recycling

8.1.2.1 Aluminium recycling

Aluminium is one of the most important non-ferrous metals in Europe, with a complete and thriving value chain ranging from primary production to recycling and semi-finished product manufacturing. This value chain is characterised by a mix of large multinational companies operating smelters and rolling mills, and a much larger number of small and medium-sized enterprises (SMEs), particularly in extrusion and recycling (*Aluminium Industry*, 2025). Together, these actors form an integrated network across Europe, with facilities spread throughout all major industrial regions (see Figure 8-3).

Like steel, two main routes dominate aluminium production (*Aluminium Industry*, 2025):

- Primary aluminium smelting, which relies on alumina (derived from bauxite) and is highly energy intensive.
- Secondary aluminium production, which uses scrap as input. This route is far less energy intensive requiring only about 5% of the energy of primary smelting.

Compared to steel, aluminium production in Europe is far more affected by energy prices, which has led to a decline in domestic primary production and a growing reliance on imports. In 2015, only around 10% of the EU's aluminium input originated from domestic primary production, with the majority covered through imports and secondary production (European Commission. Joint Research Centre, 2018). In the year 2021, only 7% came from domestic primary production and about 39% of the aluminium supply came from recycling, with more than half (54%) being imported (*Aluminium Industry*, 2025). This makes aluminium recycling critical to Europe's aluminium system, both for supply security and climate performance.

Recycling draws on a wide variety of post-consumer and industrial scrap streams, including used beverage cans, automotive components, and building materials. Scrap flows, however, are subject to both volume and quality constraints. For example, Austria's case shows that although the in-use stock of aluminium continues to grow, not all demand can be met with recycled scrap because of alloy mismatches between available secondary aluminium and required semi-finished products (Buchner et al., 2017). These qualitative challenges are partially overcome through international scrap trade, which balances differences in alloy composition, showing not only for Austria, but also for the EU that scrap prices have been clearly below the prices of imports in most years (Buchner et al., 2017).

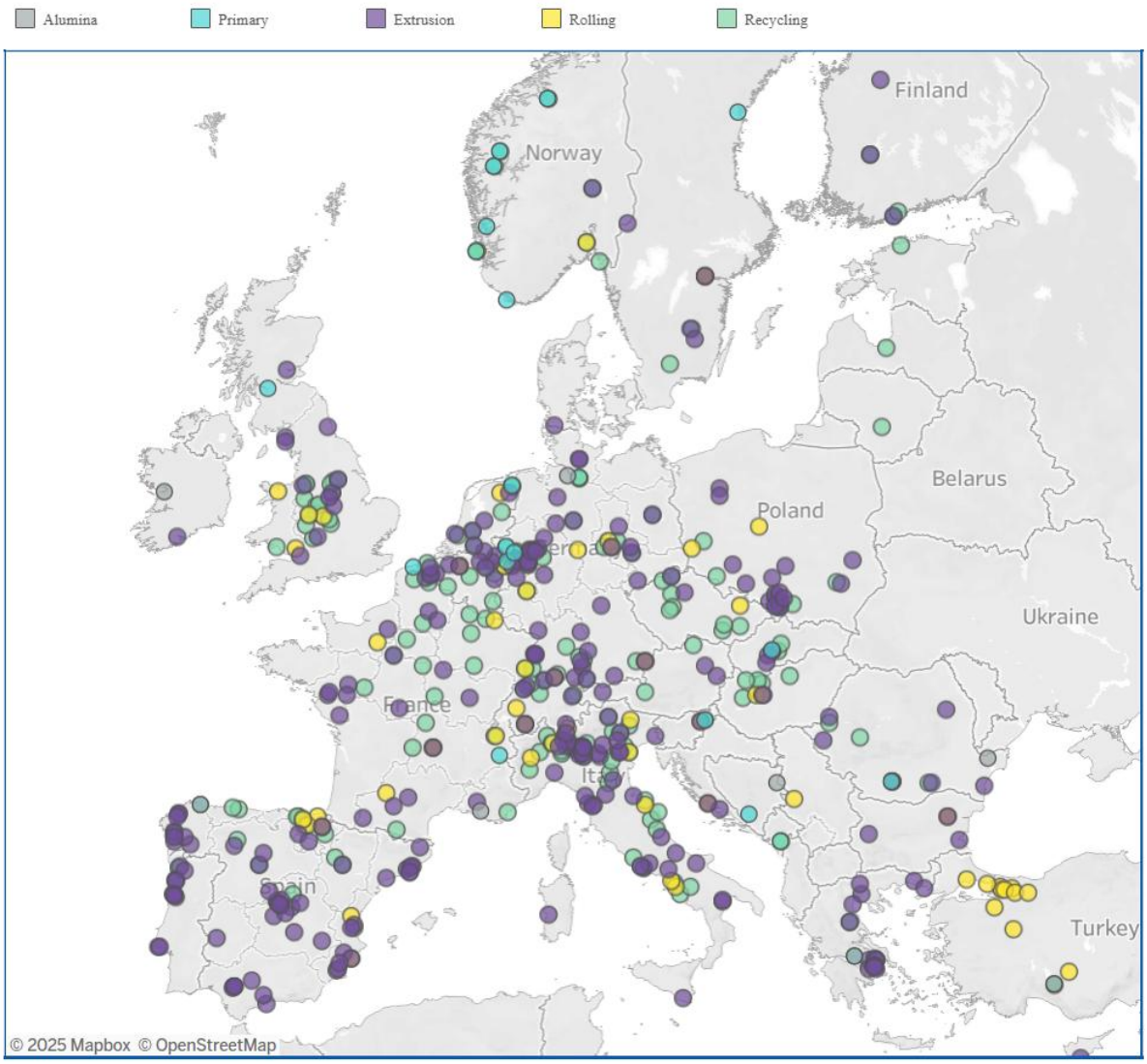


Figure 8-3: Map of EU aluminium production sites, including refining, primary production, extrusion, rolling and recycling. (*Aluminium Industry*, 2025)

8.1.2.2 Copper recycling

Copper is one of the most widely used non-ferrous metals in Europe and one of the most recycled of all metals. Thus, nearly all copper products can be recycled over and over again without loss in product properties (Samuelsson & Björkman, 2014). It is applied across numerous sectors, ranging from electrical and electronic equipment to automobiles, plumbing, and building infrastructure.

Similar to aluminium, copper production in Europe follows two main routes (Samuelsson & Björkman, 2014):

- Primary copper production, which starts with mining and refining of copper ores and concentrates. Within the EU, mine production is limited and concentrated in a few Member States such as Poland, Spain, Sweden and Bulgaria. Overall, the EU relies heavily on imports, with an average import reliance of 48% for extraction and 17% for refined copper between 2016–2020 (SCRREEN2, 2020).
- Secondary copper production, which uses scrap as input. Scrap can be classified into "new scrap" from manufacturing and semi-fabrication, and "old scrap" from end-of-life products such as cables, pipes, vehicles, and electronic waste. Depending on quality, high-grade scrap

can be remelted directly, while lower-grade fractions require refining through similar processes as in primary smelting (Samuelsson & Björkman, 2014).

Europe has a well-developed recycling sector that covers a wide range of scrap streams. Typical examples include pure copper scrap (>99% Cu), brass and bronze alloys, automotive shredder fractions (60–65% Cu), and electronic waste (5–30% Cu). In primary smelters, scrap is also used as a coolant in ore-based production, while specialised secondary smelters treat lower-grade materials such as slags, ashes, and residues (Samuelsson & Björkman, 2014).

Despite the high circularity of copper, the EU strongly remains dependent on imports for primary supply, and significant quantities of scrap are still exported outside Europe. Closing these loops more effectively is essential to ensure long-term supply security for a metal that is indispensable for the energy transition, telecommunications, transport, and modern infrastructure (SCRREEN2, 2020).

8.2 Separation of the fluoropolymers

Across the different metals, scrap preparation begins with mechanical operations such as shredding, sorting, and cleaning. During this stage, visible coatings, plastics, and insulation materials can be mechanically stripped, granulated, or otherwise separated. In copper recycling, for instance, granulators are used to strip fluoropolymer insulation from wires. However, the specific processes can be product specific, e.g. in the recycling of vehicles, fluoropolymer residues are likely to be directed to the automotive shredder residue (ASR) or fluff fraction. After size reduction, several separation techniques are applied, typically consisting of air classification, magnetic separation, Trommel separation, eddy current separation and dense media separation (Vermeulen et al., 2011). After these separation steps, ASR mainly consists of textiles, foam, plastics, rubber, cellulose and other smaller fractions (<30mm) that are highly mixed and therefore is typically incinerated (Mancini et al., 2014). Due to the differing properties of fluoropolymers and metals, it can be assumed that fluoropolymers are separated in a similar manner to other polymers that enter metal recycling facilities. However, in some products fluoropolymers are applied in a way that are difficult to remove, e.g. coated metal sheets, or fluoropolymer-containing attachments. In these cases, fluoropolymers are sent to a high temperature smelter for metal recovery, which can be considered as thermal destruction (CONCAWE, 2024).

8.2.1 Process details related to metal recycling

After entering the furnace, fluoropolymer are subject to high temperatures, especially for copper (Cu melting point: 1084°C), and steel (steel melting point: 1375° – 1530°C, depending on steel type, cast iron: 1204°C) (Metal Supermarkets, 2025). For aluminium, the melting point is around 660°C, so that removal of thicker layers fluoropolymer coating could be considered prior to melting. However, no reliable information was found regarding such removal. Although the melting temperature of aluminium is 660°C, Tsakiridis (2012) reports that the corresponding waste gas temperature is around 1000°C, which would be sufficient to thermally destroy the fluoropolymer coatings. Impacts on the quality of the metals are therefore not to be expected.

Quality deterioration in recycled steel is typically associated with the quality of scrap input. Haupt et al. (2017) discuss contamination primarily in regard to non-volatile components that can end up in the recycled steel. In particular, tramp elements such as copper, nickel, and tin, which melt at lower temperatures than steel, remain in the melt during recycling and cannot be removed, thus impairing steel quality. While coatings impact the sorting of metals, this represents a different and less well-characterised mechanism of potential quality impact. If fluoropolymer-coated or otherwise coated components are not effectively separated during preprocessing(e.g. visual sorting or density separation), mis-sorted particles could enter the recycling stream and potentially affect metal quality. However, the extent to which such effects occur in practice remains uncertain and would require further investigation.

Considering the main inputs and outputs of different furnace designs, it can be stated that different output gases are mentioned, including NO_x, CO_2, CO, HF, organic air pollutants and HC (see Table 8-1).

Table 8-1: Main inputs and outputs for different furnaces, as stated in the working document in the Best Available Techniques (BAT) Reference Document for the Smitheries and Foundries Industry (JRC, 2024).

Type of furnace / metal	Input	Output
Cupola furnace / ferro-alloys	• Ferrous material (iron pigs, sponge iron, steel scrap, foundry returns …) • Alloying metal (ferro-alloys …) • Flux (limestone…) • Energy (coke, gas, oil, electricity) • Oxygen • Cooling water • Water	• Metal alloy (cast iron) • Dust (metal content) • CO/CO_2, SO_2, NO_X • HF • Dioxins, furans • Organic pollutants • Slag • Waste refractory lining
Electric arc furnace / ferrous material	• Ferrous material (steel scrap, foundry returns swarf, pig iron …) • Alloying metal (ferro-alloys …) • Flux (limestone …) • Energy (electricity, gas, oil) • Oxygen • Electrodes	• Metal alloy (cast steel) • Dust (metal content, refractory) • NO_X, CO_2, CO • Organic air pollutants, HC • Metal oxide fumes • Slag (CaO, SiO_2, MgO) • Waste refractories
Rotary furnaces / steel, iron	• Ferrous material (iron pigs, steel scrap, swarf, • foundry returns …) • Alloying metal (ferro-alloys …) • Carburising agents, flux • Energy (electric, oil, gas) • Cooling water	• Metal alloy (cast iron) • Dust • Organic and metallic fumes • Slag • Refractory waste
Induction furnace / steel	• Ferrous material (iron pigs, steel scrap, swarf, • foundry returns …) • Alloying metal (ferro-alloys …) • Carburising agents, flux • Energy (electric) • Cooling water	• Metal alloy (cast iron, cast steel) • Dust • Organic and metallic fumes • Slag • Refractory waste
Induction furnace / aluminium	• Aluminium ingots, foundry returns • Electrical energy • Cooling water	• Molten aluminium • Dust • Used refractory

Depending on the furnace, and the input materials, the outputs from the furnace can be slightly different. HF gas is mentioned only for the copper furnace.

(Fuge, 2019) describes fluorite (CaF_2) as an intentional input in the steel processing as a flux, improving the fluidity of the melt. Further he describes AlF_3 as intentional input into aluminium smelting furnaces.

Even though the residence time varies depending on the metal and furnace, it is stated in the BREF document, waste gases must remain at >800 °C for about 2 seconds residence time to guarantee complete oxidation. For the thermal oxidation it is explicitly stated as an abatement technique that combustible compounds in waste gases are oxidised by heating with air or oxygen above their auto-ignition temperature and holding them at high temperature long enough to ensure complete conversion to CO_2 and H_2O, with typical operating temperatures between 800 and 1,000 °C (JRC, 2024). This is expected to equate to complete destruction of any organic compounds that may be present in the waste gases.

Further, to control air pollution a sequence of techniques is used. Depending on the furnace design this can include post-combustion chambers, cyclones, fabric filters, dry scrubbing with lime or sodium bicarbonate, or wet scrubbers, e.g. bag filters are common for particulate removal, while lime injection neutralises acidic gases like HF and HCl. Depending on the design, e.g. for cupola furnaces, post-combustion can take place directly in the cupola shaft, for rotary furnaces, post-combustion is carried out using an afterburner installed between the furnace and the heat exchanger (JRC, 2024).

For other residuals, it can be stated and as it is shown in Table 8-1, slag, dusts, dross, sludges, and spent refractory are typical other outputs. For the cupola furnace, cupola slag (40–80 kg/t liquid iron) contains high SiO_2 and CaO. EAF slags have varying compositions of CaO, MgO, SiO_2, and MnO, and may be reused in construction if leaching is controlled (JRC, 2024).

Overall, fluorine from scrap most likely is either bound in the slag or in air pollution control residues as calcium/aluminium fluoride, rather than being released to the environment. Steelmakers historically even added fluorspar (CaF_2) as a slag flux, which means that means steel furnaces are routinely use and manage fluorine in the system (Wu et al., 2011).

9. Fluoropolymer recycling (current practice)

The waste management option, which is used to the lowest extent for fluoropolymer containing waste, is recycling. The following chapter addresses current practice but also focuses to highlight the reasons for limited recycling.

For the discussion of recycling, three different recycling approaches need to be considered. **Primary recycling** reprocesses relatively pure waste into products of similar quality and function, **secondary recycling** mechanically reprocesses more heterogeneous waste into lower-grade materials or different products, and **tertiary recycling** uses thermochemical processes to depolymerise waste into monomers or basic chemicals that can be used again as feedstock.

Key messages

- Recycling of fluoropolymers is technically feasible but, in practice, largely limited to clean pre-consumer waste. Processing and production scrap of PTFE and melt-processable fluorothermoplastics (FEP, PFA, ETFE, PVDF) are recycled to some extent.
- Post-consumer fluoropolymer recycling is the exception. For most end-of-life products, fluoropolymers are not recycled but managed via municipal waste-to-energy combustion or landfill.
- Generally, fluoropolymers can be recycled in the same or similar way as other plastic polymers.
- The very low fluoropolymer share in mixed waste streams and their use as small parts in composite products are major structural barriers. fluoropolymers account for <0.01 % of total waste by weight (Conversio Market & Strategy, 2023) and are usually embedded in other materials, making separate collection, identification and sorting technically complex and economically unattractive with current systems.
- The recycling of polymer streams in which fluoropolymers could be present in small amount due to difficulties with separation might require clear guidance and further research, knowledge transfer from upcycling technologies could be used in this regard
- Melt-processable thermoplastics (FEP, PFA, ETFE, PVDF) are, in principle, easier to recycle than non-melt-processable PTFE and cross-linked FKM, yet post-consumer recycling is rare or not practised for all of them (only limited for PVDF, e.g. in batteries).
- Recent environmental fate data reduce concerns about PTFE micropowders. New studies on microparticulate PTFE show no degradation to non-polymeric PFAS under tested conditions, supporting the view that such powders do not transform into smaller, mobile PFAS substances of concern (Henry & Timmer, 2025).
- Tertiary recycling (“upcycling”) via thermo-chemical depolymerisation is technically possible, especially for fully fluorinated fluoropolymers. Pyrolysis of PTFE and fully fluorinated thermoplastics (PFA, FEP) can recover monomers such as TFE and HFP, enabling the production of new fluoropolymers.
- However, TFE is reactive, can decompose explosively and is classified as a carcinogen. As a result, its production, purification, storage and handling require strict safety measures. Because of its explosive behaviour, transport is difficult, generation in an upcycling process and subsequent polymerisation preferably need to occur on the same site. This applies not only to upcycling routes but is equally characteristic of conventional virgin PTFE production. In addition, storing TFE, especially in liquefied form, is energy-intensive and increases operating costs.
- At end of life, fluoropolymers represent a secondary fluorine reservoir. In established treatments such as hazardous waste incineration, fluorine is largely mineralised and captured as inorganic fluoride salts (e.g. CaF_2); while not equivalent to mined fluorspar in all respects, such recovered fluorides may, in some cases, be further processed and reintroduced into parts of the fluorine value chain, potentially reducing demand for primary fluorspar – a critical raw material.
- Barriers include legal and regulatory uncertainty, immature collection infrastructure, and stringent quality requirements. Upcoming PFAS-related regulations and sectoral rules create uncertainty about the acceptance of recycled fluoropolymer content. Many high-end applications only accept virgin-grade material, further limiting recyclate markets.
- In Europe, there is no established market for secondary fluoropolymer materials and no efficient value chain to process them.

- Information gaps along the value chain are barriers for recycling. Many actors (especially downstream users and waste managers) lack transparency on what is technically recyclable and what fluoropolymer parts are included. Decisions are often delegated to third-party waste contractors, who base choices on contamination, local rules and costs.

What does recycle, or upcycle or reuse mean

The term **"recycling"** is defined in the EU Waste Framework Directive 2008/98/EC (WFD) According to Article 3(17) of the WFD, recycling means "any recovery operation by which waste materials are reprocessed into products, materials, or substances, whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations."

The definition emphasises that recycling involves the reprocessing of waste materials, whether for the same or different uses, but excludes energy recovery or conversion into fuels. Hence, recycling fluoropolymers involves processes where waste fluoropolymers are reprocessed into new products, materials, or substances. This could involve mechanical recycling and recycling techniques specific to fluoropolymers. The EU supports solutions to address plastics management issues e.g. by favouring the development of new sorting and recycling technologies (Plastics strategy - European Commission), which might e.g. be required for the recycling of fluoropolymers.

According to Article 3(13) of the WFD, the term **"re-use"** means "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived." The definition specifies that "re-use" applies to products or components that remain in their original form and are used again for their intended purpose, without requiring reprocessing.

Fluoropolymers are typically used in applications for which they are specifically designed (e.g., in high-performance industries like aerospace, chemical processing, and medical devices) for long-term use. Products consisting of fluoropolymers often retain their properties for extended periods and could therefore be appropriate for re-use (e.g. tubes, containers, gaskets and seals, pipe liners and other lining, hoses, etc.).

The term **"upcycling"** is not legally defined in EU Directives. The concept is commonly used in sustainability and circular-economy contexts to describe processes in which waste materials are transformed into products or materials of equal or higher functional or economic value.

From a legal perspective, such activities are assessed based on the process applied and the characteristics of the output material and may be classified as "recycling" or "re-use" under EU waste legislation. Upcycling thus contrasts with recycling as a value-oriented concept rather than a distinct legal category. In the context of fluoropolymer recycling, upcycling is described as a thermo-chemical recycling, which splits the polymer back into the corresponding monomers, which, when cleaned, can be re-used for polymerisation of neat fluoroplastics (pro-K, 2018).

Industry or CEN standards for fluoropolymer recycling

CEN Standards or industry standards for fluoropolymer recycling could not be identified.

In 2022 the European Commission notified to the European Committee for Standardization (CEN) and the European Committee for Electrotechnical Standardization (CENELEC) the new Standardization Request on plastics recycling and recycled plastics, in support of the European Strategy for Plastics in a Circular Economy. This covers plastics recycling broadly, targeting packaging, construction, electronics, vehicles, agriculture, etc. However, it does not specifically address fluoropolymers.

However, PlasticsEurope provides guidance for the safe handling of fluoropolymer resins (see Fluoropolymers Safe Handling). The guidance addresses among other, information on recycling and disposal. It states that waste polymers generated during the processing of fluoropolymer resins should be recycled whenever feasible. This recycling can be carried out directly by the producer or, on a larger scale, through specialised international recycling companies. At present, fluoropolymer

compounds that include fillers such as glass fibers, carbon, or bronze are less easily recycled than unfilled fluoropolymers; however, new applications and markets for recycled filled compounds are currently being explored. The guidance also notes that since fluoropolymers are primarily incorporated into small parts within larger products, it is generally not practical to isolate, clean, and recover these minor quantities. However, their presence does not hinder the recycling of the primary material. For instance, steel items containing limited amounts of fluoropolymer components can still be re-melted, allowing the metal to be reclaimed.

According to (Conversio Market & Strategy, 2023), the overall fluoropolymer penetration in all waste streams was less than 0.01% by weight. In comparison, plastics in total accounted for about 4.8% of the total waste collection volume (excl. mineral fractions). To enable efficient recycling, it would be necessary to separate fluoropolymers from waste streams. The low fraction of fluoropolymers in waste streams is a reason why separation of fluoropolymers can be technically and economically challenging and is not state of the art, e.g. in ELV or WEEE plastics recycling.

Box 9-1: Understanding the influence of fluoropolymer properties on recycling

To understand recycling options and pathways, it is important to be aware of different properties (see Table 1-1) of the different fluoropolymers that have an influence on recycling options.

The distinction between melt-processable fluoropolymers and cross-linked or filled materials is central in this regard. The following table show the properties of the fluoropolymers in scope of this study.

Abbreviation	Full Polymer Name	Thermoplastic	Melt-Processible	Crosslinked in commercial practice
PTFE	Polytetrafluoroethylene	**Yes**	**No**	**No**
FEP	Fluorinated Ethylene Propylene (copolymer of TFE + HFP)	**Yes**	**Yes**	**No**
PFA	Perfluoroalkoxy Alkane (TFE + perfluoroalkyl vinyl ether copolymers)	**Yes**	**Yes**	**No**
ETFE	Ethylene Tetrafluoroethylene	**Yes**	**Yes**	**Yes (selected grades)**
PVDF	Polyvinylidene Fluoride	**Yes**	**Yes**	**Yes (special grades)**
FKM	Fluoroelastomer (VDF-HFP or VDF-HFP-TFE types)	**No**	**No**	**Yes**

Melt-processable fluoropolymers can be re-melted and re-processed. For those fluoropolymers, clean production scrap and selected post-industrial waste streams can – in general - be mechanically recycled by regranulation and re-extrusion.

On the other hand, many fluoropolymer applications rely on non-meltable material (e.g. sintered PTFE) or partially cross-linked systems. Those materials cannot be re-melted into a homogeneous mix. In practice, recycling options are typically limited. For filled materials, the filler material can influence recycling options.

9.1 State of the art of recycling

The Conversio (2023) study, conducted with a European focus, examined the end-of-life pathways of fluoropolymer (FP) applications and products. It considered aspects such as the reuse of processing scrap and the recycling of both pre- and post-consumer fluoropolymer waste through mechanical methods (e.g., conversion into PTFE micropowders) or chemical processes within the EU. Key insights on the current state of recycling from this study are outlined in the following table.

Table 9-1: Key conclusions from (Conversio Market & Strategy, 2023)

The data refer to post-consumer fluoropolymer waste

- About **23.5 kt of post-consumer** *fluoropolymer* **waste** were collected in 2021, mainly from chemicals (9.4 kt), automotive (3.5 kt), electronics/semiconductors (2.7 kt), and medical/pharma (2.3 kt).
- fluoropolymers account for **<0.01% of total waste streams**.
- Roughly **3% of post-consumer** *fluoropolymer* **waste** was collected separately for recycling, with a notable share exported (e.g. to Asia).
- Only **0.81 kt of post-consumer** *fluoropolymer* **waste** were actually recycled across sectors (chemicals 0.35 kt, electronics/semiconductors 0.15 kt, medical/pharma 0.10 kt, aerospace 0.01 kt, other 0.20 kt).
- **<0.7 kt of post-consumer** *fluoropolymer* **waste** were recycled through re-grinding, sintering, or upcycling, and **<0.1 kt** through thermoplastic (mechanical) recycling.
- Post-consumer recycling is limited to **clean industrial/commercial fractions (~13 kt)**; the effectively recyclable share is much smaller.
- Recycling remains focused on **clean pre-consumer waste**; only small volumes (see above) of post-consumer material are recovered.
- Thermoplastic fluoropolymer recycling is mainly sourced from **semiconductor, chemical, and pharmaceutical equipment**.
- **20–25% of fluoropolymer producers** reprocess their own scrap, **30–35%** send it to recyclers, **15%** export within the EU, and **5–10%** outside the EU.
- **Mixed household or industrial waste** recycling is not practiced and unlikely to become feasible given the very low fluoropolymer content.
- Key actors in fluoropolymer waste handling include **ELV and WEEE dismantlers, shredder and metal recyclers, industrial service providers, hospitals, aircraft dismantlers, municipal services, and internal recycling operations**.

Pro-K (2018) provides a brochure, which provides details on the different possibilities and processes to recycle fluoropolymers. The brochure indicates that for pure PTFE, established recycling routes are available. In contrast, processors working with PTFE compounds often must send their production residues to landfill, which incurs significant disposal costs. Efficient recycling options also exist for fully fluorinated thermoplastics, but when these materials are modified with pigments or conductive additives, they generally cannot be recycled and must likewise be disposed of at considerable expense. The authors differentiate primary, secondary and tertiary recycling of fluoropolymers. In the simplest case, known as primary recycling, clean production scrap is directly reprocessed and reused with little loss of quality. Secondary recycling deals with materials that cannot be remelted and typically involves grinding or other treatments to produce powders or fillers for lower-value applications. The most advanced option, tertiary recycling, relies on thermo-chemical processes to break polymers back into their monomers, which can then be used to manufacture new, high-quality fluoropolymers (pro-K, 2018).

Based on results from the value chain survey and expert interviews, actual recycling or recovery of post-consumer waste of fluoropolymers seems to remain rare. Among respondents who acknowledged the technical possibility of recycling, most clarified that it is not performed in practice. In some cases, third-party contractors or recyclers handle disposal decisions, basing them on contamination levels, local legislation, or the cost-benefit ratio of recovery.

A few responses outlined potential downcycling or repurposing options. For example, fluoropolymer components that are worn, dimensionally distorted, or contaminated may still be used in non-critical applications or as fillers within different applications. This could enable partial value retention even if full material recycling is not feasible. Benefits such as enhanced friction reduction and thermal stability were cited as desirable properties in such filler applications.

Box 9-2: Excursion on the potential use of downcycled PTFE

In discussions about fluoropolymer recycling, true close-loop recycling (where one old pipe or gasket is converted back into the same product) is rare, particularly for post-consumer waste. Instead, one of the dominant recycling routes, especially for PTFE, involves mechanical processing into fine micropowders and using them as performance fillers in other materials. While this approach retains the fluoropolymer backbone, it does not preserve the original product function and is therefore often regarded as down-cycling rather than

material-to-material recycling. Understanding the downstream applications of those powders is important for assessing the actual scale and relevance of this recycling pathway.

Companies around the world produce extremely fine PTFE powders, with particle sizes in the range of one to a few dozen micrometres. These powders can be made either from virgin PTFE or from carefully controlled scrap and offcuts that are degraded and micronized rather than discarded.

(Drobny & Ebnesajjad, 2023) mention that PTFE production facilities generate various unusable materials that cannot be marketed as top-quality resin. Examples of such off-spec materials include deviations in particle size, apparent density, tensile strength, and other properties. These materials are designated as second grade and are typically directed to the recycling or reuse sectors. In certain instances, they are used as input for the creation of fluorinated additives like micropowder. The particle size of micropowder is a critical characteristic for many applications.

In practice, this means that once the material has been turned into powder, it could become an additive for various products like inks, paints, plastics or lubricants.

PTFE micropowders are promoted as additives (Shamrock Technologies, 2025) for inks. Closely related to printing inks are paints and industrial coatings, another important destination for fluoropolymer powders. PTFE micropowders are marketed as performance additives for powder coatings on metal components, for coatings on machinery, and for various specialty lacquers and varnishes. The role is similar to inks: a small fraction of PTFE powder in a coating can reduce friction, improve scratch and abrasion resistance, and add a degree of non-stick behaviour (AGC, 2019; Dreyplas, 2025).

It is important to stress, that this is different from the well-known non-stick pan coatings, which are usually based on thicker PTFE layers applied in different ways and are typically made from virgin material.

Another major cluster of applications is in plastics themselves. Here, PTFE powders are added in low percentages to conventional engineering plastics such as polycarbonate and polyamides (nylons), as well as to other thermoplastics, to reduce wear and friction in moving parts. (AGC, 2025; Fluorotech, 2025)

In plastic applications, the PTFE powder can be a blend of virgin and recycled material, or in some cases entirely recycled-based, depending on the supplier and the regulatory requirements of the final product.

PTFE micro powders are further marketed as additives for rubber compounds to improve wear, reduce friction and enhance certain mechanical properties (Fluorotech, 2025; TOPDA, 2020). Again, the fluoropolymer content is low compared with the base rubber. Depending on the grade, the PTFE powder may be produced from virgin or recycled PTFE, but the performance requirements for many technical rubber products seem to be compatible with recycled-derived powders.

Suppliers of PTFE micropowders further list grades designed for lubricants and greases (Everlon, 2025).

Publicly available documents rarely provide precise percentages for how much of the PTFE powder market is based on recycled feedstock, or what share of total fluoropolymer end-of-life flows this represents. Producers typically speak of “recycled-based” lines alongside “natural prime” (virgin) lines, and present recycled content as an option rather than the default.

A large proportion of respondents to the survey within this project lack certainty regarding fluoropolymer recyclability, suggesting gaps in knowledge or clarity across the industry. This uncertainty may reflect limited availability, accessibility, or consistency of information on fluoropolymer recycling pathways along the supply chain.

9.1.1 Available recycling capacities and technologies

Based on information from expert interviews and information provided in (Améduri & Hori, 2023) and (Conversio Market & Strategy, 2023), there are a number of companies carrying out recycling of fluoropolymers including fluorinated thermoplastics (Aturon, 2025; MINGA, 2025), PTFE (Daikin, 2025; Fluormetall, 2025; Shamrock Technologies, 2025; United Polymer Mixers, 2025) or upcycling of PTFE and selected PTFE compounds and fully fluorinated thermoplastics (3M, 2025). The latter is currently not operating. One company mentioned in the Conversio study confirmed termination of the fluoropolymer recycling business activities in the meantime. Another one explained that fluoropolymer recycling is a business model for them in which the actual recycling is outsourced to

a service provider (Polychromos, 2025). The recycled material is mainly sold to Asia. The third company mentioned that they do not process post-consumer fluoropolymers but occasionally trade post-industrial recycled PTFE and PVDF. In practice, there is recycling of processing and production waste but typically no recycling of end-of-life post-consumer recycling.

In the following, different recycling approaches are explained in more detail. It starts with primary recycling, in which the material is not changed but mechanically sorted and continues with secondary recycling in which materials are modified. Finally, the current tertiary recycling capabilities - basically a reprocessing by chemical processes or heat - of fluoropolymers are explained.

9.1.1.1 Primary recycling

Primary recycling refers to the direct reprocessing of uncontaminated polymer waste, typically from pre-consumer sources. This route generally uses extrusion or other standard thermoplastic techniques, applied to clean and uniform polymer streams.

As an example, primary recycling of PTFE involves collecting and grinding sintered waste into powder suitable for reuse. Pre-sintered PTFE, however, can only be reprocessed under combined heat and pressure, as in ram extrusion (Dams & Hintzer, 2016). The physical properties (e.g. tensile strength and elongation as well as cold flow) of regenerated PTFE differ significantly from those of virgin PTFE (Améduri & Hori, 2023).

Another method of primary recycling is paste extrusion, a specialised cold processing method used primarily for PTFE fine-powder resins in which PTFE powder is blended with a volatile lubricant to form a "paste", preformed into a billet, and then extruded through a die at near ambient temperature before lubricant removal and sintering to fuse the structure (Ochoa & Hatzikiriakos, 2005). Based on an expert interview, around 50% of PTFE recycling is via paste extrusion. Processing waste which arises from paste extrusion, and which is not sintered can cause problems during recycling. During paste extrusion, the PTFE is shaped under pressure but not exposed to the high temperatures needed for sintering, leaving the material in its raw, unsintered state. As a result, the waste can have irregular particle sizes, densities, and mechanical strengths. These inconsistencies make it difficult to recycle the material uniformly and complicate the production of new products with predictable and reliable properties.

To overcome these challenges, specific treatments are necessary to render the waste suitable for recycling or upcycling. These treatments focus on improving material properties, removing contaminants, and stabilising the PTFE, thereby facilitating its reuse. Possible steps include grinding and sorting, sintering or re-extrusion.

Most melt-processable fluoroplastics, such as PVDF can be recycled in a similar way to other commodity thermoplastics, that is, by re-melting through extrusion (Wahlström et al., 2021).

Regarding the fluoropolymers in scope of this study, PTFE is not processed using traditional thermoplastic methods such as injection molding. Where high-purity material streams are available, mechanical reprocessing may be feasible. This has been demonstrated in the literature for PFA and is also reported commercially for PVDF (AGC, 2018; ARKEMA, 2023; Guenoun et al., 2020; Romoaldo et al., 2023).

When processing conditions are carefully managed, many polymers can withstand multiple rounds of primary mechanical recycling without significant deterioration in performance (Améduri & Hori, 2023).

9.1.1.2 Secondary recycling

Secondary recycling involves breaking down high-molecular-weight PTFE into micropowders. This reduction in chain length can be achieved through thermo-mechanical degradation or by exposing the material to high-energy radiation. In practice, irradiation methods often employ the same types of sources used in medical technology, such as gamma rays from cobalt-60 or electron beams from

e-beam accelerators. Unlike primary recycling, secondary recycling requires the polymer waste to be sorted, reduced in size, and then reprocessed through methods such as extrusion, sintering, or similar techniques.

9.1.1.3 Tertiary recycling (upcycling)

In tertiary recycling - often described as upcycling - PTFE & fully fluorinated thermoplastics like PFA and FEP are subjected to pyrolysis in an inert environment, which breaks down the polymer chains into their original monomers, most notably tetrafluoroethylene (TFE) and hexafluoropropylene (HFP). This method is particularly versatile because it allows the recovery and repolymerisation not just of uniform PTFE, but also of fully fluorinated thermoplastics like PFA and FEP, as well as compounded varieties that contain mineral fillers. However, implementing this recycling pathway calls for specialised fluoromonomer recovery infrastructure, so only facilities with the necessary equipment and technical capability are capable of performing this process (pro-K, 2018).

In thermo-chemical pathways such as pyrolysis, the polymer is decomposed into its constituent monomers. For instance, pyrolyzing PTFE in an inert atmosphere yields high quantities of monomers like TFE and HFP, which, once purified, can be reused for polymerisation (Améduri & Hori, 2023). There is no quality loss described for the recycled materials (Schmidt-Rodenkirchen et al., 2023). Technical barriers, however, exist that need careful consideration and that limit the commercial application of upcycling technology (see chapter 4.3).

Some sources use upcycling and chemical recycling synonymously, which can create confusions. The following box explains the controversies in this regard.

Box 9-3: The term "chemical recycling"

The term "chemical recycling" needs to be used with care, because it is not always understood in the same way.

In most industrial and policy contexts, chemical recycling refers to processes that break polymers down into smaller molecules - such as monomers, oligomers or basic chemicals - that can be used again as feedstock for new materials. This definition fits well with current large-scale practice for polyolefins and PET. From this perspective, chemical recycling is "relevant" today mainly for these high-volume plastics, whereas comparable technologies for fluoropolymers are still at an early, mostly experimental stage due to their chemical and thermal stability and the associated technical and environmental challenges.

At the same time, some stakeholders use "chemical recycling" in a broader sense, closer to "upcycling." In that usage, any process in which fluoropolymer waste is chemically transformed into a new, higher-value product - whether or not the original monomer or polymer is recovered - may be described as chemical recycling.

To avoid confusion, this report distinguishes between "chemical recycling in the strict sense" meaning depolymerisation to monomers or basic feedstock suitable for producing new fluoropolymers or other base chemicals, and "chemical upcycling" meaning value-adding chemical transformations that do not necessarily aim at closed-loop recovery.

For fluoropolymers, the former remains largely at the R&D stage, while the latter may offer more realistic short- to medium-term options.

9.1.2 Current recycling practices for different fluoropolymers, its driving factors and barriers

While section 9.1.1 provided a picture on available recycling processes, the following section should bridge the gap to understand, which processes are followed in a post-consumer phase. Therefore, the survey participants were asked to reflect on if the fluoropolymers used in their articles can be recycled and if this possibility is used, meaning are they recycled or recovered in cases in which it would be possible. The feedback is summarised in the following.

Box 9-4: Feedback on recycling practices

Known recycling processes were indicated. A few respondents referenced ongoing pilot projects that show promising test results but remain at an early stage of industrial scaling.
There is a consensus among stakeholders that **not all fluoropolymers are equally recyclable**. The overall pattern that emerges is shaped by polymer structure (thermoplastic vs. elastomeric), processing characteristics, and material purity or contamination. The distinctions between melt-processable fluoropolymers and cross-linked or filled materials are key to understanding the feasibility of recycling (see Box 9-1).
Thermoplastics are considered theoretically as being easier to recycle. Respondents noted that melt-processable fluoropolymers like PFA and FEP can be recycled easily, with some companies stating that they recycle nearly 100% of their internal scrap. This is done either in-house or via recycling partners. These materials can be re-melted and reprocessed, making them more compatible with mechanical recycling processes.

PTFE, however, is described as more difficult to recycle, despite being thermoplastic. This is because PTFE does not melt under normal processing conditions.

Several respondents indicated that cross-linked fluoropolymers (e.g., FKM, FFKM) are more challenging to recycle. One expert indicated that mechanical recycling is not possible, while another stressed that different recycling options would need to be considered than e.g. for PTFE.

It was acknowledged that identification and sorting fluoropolymers in mixed waste streams remains a major challenge. The lack of visual differences or labelling means that current automated systems cannot reliably separate different fluoropolymer types, making post-consumer recycling difficult or uneconomical. In this context, even technically recyclable materials may end up being incinerated.

In the following, recycling options for different fluoropolymers are elaborated in more detail not necessarily focusing on post-consumer products. In order to get more insights why recycling rates are currently low particular emphasis is placed on **drivers (supporting factors)** and **barriers (hindering factors)** that influence the implementation and scaling of recycling approaches.

9.1.2.1 Recycling of PTFE

PTFE is formally categorised as a thermoplastic, but its processing behaviour differs from standard thermoplastics. Owing to its high melting point (approximately 327 °C) and exceptionally high melt viscosity, it cannot be shaped through conventional melt-processing methods such as extrusion or injection molding (Schlipf & Schwalm, 2014; Wahlström et al., 2021). This unusual processing behavior is itself a **barrier** for conventional primary recycling routes based on remelting and re-extrusion. For this reason, PTFE is generally not shaped by conventional methods but instead manufactured through pressure sintering, after which the final geometry is achieved by machining.

PTFE waste can be converted into fine powder, which may then be processed through compression molding under pressure or employed in ram extrusion. Prior to grinding, the material is typically shredded and heated to eliminate volatile impurities. Following grinding, the resulting powder is subjected to acid treatment – commonly with mixtures such as nitric and perchloric acids – to remove inorganic residues, after which it is thoroughly washed (Wahlström et al., 2021). Lakshmanan & Chakraborty (2015) describe different techniques of PTFE recycling, including generation of micropowder with irradiation as well as pulverising PTFE scrap without irradiation.

A central **driver** for PTFE recycling is the fact that PTFE is the most widely used fluoropolymer. This broad use implies a large absolute waste stream and thus a significant potential resource base. In addition, production generates substantial amounts of scrap and the material itself is relatively costly. These factors provide strong economic incentives for recycling, and recycling practices in this field therefore developed early on. (Drobny & Ebnesajjad, 2023) divide the basis for recycling into two different categories: PTFE resin-based material from polymer manufacturers and part scrap from processors and fabricators. They indicate that off-spec material – for example, not meeting specifications for particle size or apparent density – is downgraded from first-grade to second-grade

material, which then becomes a valuable source for the recycling/reuse market. This continuous stream of off-spec but high-quality material is another **supporting factor** for PTFE recycling.

However, contamination can be seen as a major **barrier**. According to (Drobny & Ebnesajjad, 2023) most PTFE scrap is contaminated by organic or inorganic substances, including pigments, oils, or greases. Cleaning steps must be considered before reprocessing. These cleaning steps can limit the economic viability of recycling, in particular for lower-value applications or smaller waste volumes.

A further potential **barrier** arises from the emission profile of some recycling processes. Under electron-beam irradiation, PTFE chains undergo bond cleavage, generating highly reactive radical species that can subsequently form hydrogen fluoride. The resulting HF-containing off-gases must be effectively captured and extracted from the processing environment. Studies have also shown that other long-chain PFAS may be formed during the process (ECHA, 2015). According to (Wahlström et al., 2021) citing (Hintzer & Schwertfeger, 2014; Makuuchi & Cheng, 2012), the production of hydrogen fluoride is relatively limited when PTFE is exposed to gamma radiation, since the irradiation intensity is much lower than that achieved with electron beams.

Industry typically refers to recycled PTFE as reprocessed PTFE, repro PTFE, or mechanical-grade PTFE. The recovered material, which is usually in powder form, is often blended with virgin PTFE and applied in cost-sensitive areas where the highest purity is not necessary – for example, in non-critical chemical, mechanical, or electrical components. This partial substitutability of virgin PTFE in non-critical applications is an important **driver**, as it allows recyclate to capture existing market demand and generate cost savings. At the same time, not all markets can use reprocessed PTFE. Some sectors demand strict safety and purity standards, so that only virgin-grade PTFE can be used. This is true for pharmaceuticals, some food-contact products, cosmetics, and medical devices (Lakshmanan & Chakraborty, 2015) as cited in (Wahlström et al., 2021).

Another **barrier** is that not all recycled PTFE streams are suitable for closed-loop use.

In primary mechanical recycling, clean sintered PTFE waste can be collected, grounded and reprocessed into regenerated PTFE. Although it can be used in certain PTFE applications its properties are quite different to the ones of virgin PTFE. As elaborated in Wahlström et al. (2021), citing (Dams & Hintzer, 2016; Hintzer & Schwertfeger, 2014; Lakshmanan & Chakraborty, 2015), recycled PTFE cannot be moulded in the same way and does not possess the same plastic properties as virgin PTFE.

Secondary recycling processes on the other hand degrade PTFE into low-molecular-weight micropowders. The degradation produces low-molecular-weight PTFE, which is subsequently processed into fine micropowders through milling (Hintzer & Schwertfeger, 2014) as cited in (Wahlström et al., 2021). Degradation through irradiation can be carried out using electron beams, X-rays, or gamma rays. Pro-K (2018) explains that irradiation makes the PTFE friable and is therefore typically followed by a grinding step to obtain the desired particle size; this treatment drastically shortens the polymer chains to roughly one percent of their original length and thus significantly alters the material characteristics. As a result, the degraded PTFE can no longer be used in conventional PTFE applications. The micropowders produced through thermal or irradiation-induced degradation are functional across a broad temperature range, from about –190 °C up to 250 °C, and are valued for imparting non-stick behavior, enhancing lubrication, increasing wear resistance, and providing reinforcement ((Dams & Hintzer, 2016; Hintzer & Schwertfeger, 2014; Lakshmanan & Chakraborty, 2015) as cited in Wahlström et al., 2021). They are therefore primarily incorporated as additives in applications such as coatings, lubricants, oils, printing inks, plastic materials, elastomers, and paints to improve sliding and processing behavior, reduce surface fouling, and support improved release effects (pro-K, 2018; Wahlström et al., 2021). The United States Food and Drug Administration considers irradiation-based degradation as a well-established method and permits the resulting micropowders to be used as additives in plastics intended for repeated food-contact applications (pro-K, 2018; Wahlström et al., 2021). This established regulatory acceptance, especially for food-contact applications, are clear **supporting factors**.

Wahlström et al. (2021) on the other hand highlight that recycling of PTFE into micropowders requires closer evaluation. The authors state that many of its applications are dispersive in nature and lead to the release of PTFE particles into indoor and broader environmental settings. This represents an emerging **barrier**, with the potential to reduce social acceptance or trigger stricter regulation in the future. However, closer evaluation has recently been provided by a study that demonstrates that such discharge of PTFE particles into the environment has not been shown to lead to environmental release of non-polymer PFAS (Henry & Timmer, 2025).

9.1.2.2 Recycling of other fluorothermoplastics

The fluoropolymers within the scope of this report – FEP, PFA, ETFE and PVDF – are thermoplastics that can be processed and recycled using conventional melt-processing methods (primary recycling). Their melt-processability is a key **driver**, as it allows the use of established thermoplastic recycling routes such as re-melting and re-extrusion of clean production scrap.

For fluorothermoplastics, several primary recycling practices are already in place. In film extrusion, trimming residues are immediately pelletised and reintroduced into the extrusion process. Material generated during start-up or shut-down, which may differ in quality from the final product, is collected as a separate fraction, cleaned, pelletised, and reused in thermoplastic processing – although its properties may limit the range of suitable applications. Nevertheless, such recycled products have gained market acceptance, with applications including tubing and clamping systems in architecture and power plant construction. These functioning in-house loops represent an important **supporting factor**.

In cases where primary recycling of fluorothermoplastics such as PFA or FEP is technically infeasible, they can instead be directed toward upcycling processes (pro-K, 2018). Alternative recycling approaches include re-grinding and sintering, as well as upcycling (see Box 9-3) of fluoropolymer wastes (Améduri & Hori, 2023), which broaden the portfolio of possible end uses.

In contrast, recycling of fluoropolymers from consumer products is still underdeveloped. A major **barrier** is that these materials are often combined with fillers or contaminated with other substances, which complicates separation and recovery (pro-K, 2018; Schlipf & Schwalm, 2014). Overall, most of the fluoropolymers in the project scope are melt-processable (except PTFE). For primary recycling, clean pre-consumer waste fractions (e.g. production waste) can be remelted and reused in manufacturing processes, whereas post-consumer recycling is typically not carried out in practice due to various constraints (see chapter 4.3). Post-consumer waste may instead be more suitable for tertiary recycling.

The following table provides details for the thermoplastic fluoropolymers in the scope of this project.

Table 9-2: recycling of thermoplastic fluoropolymers

Thermoplast	Melt properties	Details related to recycling
FEP	melt-processable fluoropolymer with a melting temperature around 260–282 °C (Teng, 2012)	Clean production waste (e.g. from film or tubing extrusion) can be regranulated and reprocessed. For waste such as sprues generated during injection moulding of PFA or FEP, the material is typically ground, cleaned, and following granulation fed back into injection moulding or extrusion (Schlipf & Schwalm, 2014). Here, the technical feasibility of re-melting is a **driver**, while cleaning demands and property control act as **barriers** when high-quality applications are targeted.
PFA	melt-processable fluoropolymer with a melting temperature around 302–310 °C (Teng, 2012)	Although PFA represents only a small share of end-of-life waste, its processing can generate scrap rates of up to 30 %, creating an **economic driver** for recycling (Améduri & Hori, 2023). (Romoaldo et al., 2023) investigated closed-loop recycling of PFA. The authors incorporated recycled PFA (PFAr) at levels of 5–100 wt.% into virgin PFA and studying thermal, mechanical, rheological, colour, and chemical resistance properties. Colour stability and chemical resistance remained largely unaffected for all compositions, but higher PFAr contents (≥50 wt.%) led to

Thermoplast	Melt properties	Details related to recycling
		noticeable declines in mechanical performance. This was especially true for tensile strength and elongation at break. Blends containing up to 10 wt.% PFAr were found to be suitable for reintroducing PFA residues via mechanical recycling without significant property loss. This demonstrates a **supporting factor** (technical viability at low recyclate content), while property deterioration and colour changes at higher contents represent **barriers** to high-percentage closed-loop recycling.
ETFE	melt-processable fluoropolymer with a melting temperature around 254–279 °C (Teng, 2012)	Clean production scrap can be re-melted and reused, supported by its thermoplastic nature and homogeneous waste streams. By contrast, strongly weathered, multilayer or highly contaminated ETFE products at end-of-life are more difficult to recycle and thus represent a **barrier** to broader implementation of post-consumer recycling.
PVDF	melt-processable fluoropolymer with a melting temperature around 155–192 °C (Teng, 2012)	Clean production waste can be re-melted and reused, and there are also efforts to recover PVDF from batteries using solvent-based processes. The growing volume of PVDF in battery applications is a potential **driver** for dedicated recovery routes, although the complexity of battery systems and contamination with other components constitute important **barriers**. PVDF can be processed and reused multiple times – up to five cycles – without significant changes in its mechanical or physical properties (Améduri & Hori, 2023). In manufacturing, it is common practice to incorporate up to 20 % reprocessed PVDF into injection-moulded and extruded items. Reports of 3D printing parks using recycled PVDF to create bridges further illustrate practical implementation. PVDF exposed during use is also considered safe for further reuse (Améduri & Hori, 2023). These findings provide **supporting factors** for PVDF recycling.

PVDF copolymers are furthermore effective as polymer processing and recycling aids (PPRA) in polyolefin products such as films, cables, pipes and moulded components. They enhance surface finish, increase throughput, reduce extruder pressure and die build-up, improve material flow, support consistent gauge control, and enable processing at lower temperatures (Peters & Lowrie, 2022). While such fluoropolymer-based additives were initially developed for virgin polyethylene and polypropylene, advances in recycling show that similar benefits apply to recycled materials as well (Améduri & Hori, 2023). In this context, PVDF-based processing aids act as an **indirect driver** by improving the processability and quality of recycled polyolefins and supporting higher recycle shares.

Arkema reports that, with improved processes, the proportion of recycled material in products like films, cables, pipes and moulded parts can be increased from the previous 20–30% up to 90–100%, without noticeable loss in performance. Using PVDF-based processing aids in recycled polyolefins therefore results in properties that closely resemble those of virgin resin with processing aids. PVDF and vinylidene fluoride copolymers are thus valuable for boosting the reprocessing efficiency of high-volume polyolefins (Améduri & Hori, 2023), representing a significant **supporting factor** for both PVDF and polyolefin recycling.

9.1.2.3 Recycling of fluoroelastomers (FKM)

FKM are thermoset materials. In contrast to thermoplastics, they cannot be remelted and reshaped because their molecular structures contain cross-links. Therefore, they are not suitable for primary recycling processes based on melting and reprocessing, which represents a fundamental **barrier** for conventional recycling approaches.

According to Améduri & Hori (2023), the recycling of fluorinated elastomers is challenging, but two approaches have been recognised as suitable for industrial application: (i) blending finely ground fluoro-rubber powder with virgin rubber, and (ii) mechanically devulcanizing FKM followed by compounding with virgin rubber. Both strategies have demonstrated feasibility and can maintain

good thermal stability and mechanical performance (Schuster et al., 2022), which constitutes an important **supporting factor** for FKM recycling.

The fluoro-rubber vulcanized powder recycling process represents an applied technique for reclaiming polymers and rubber. During molding operations, FKM waste such as press flash, runners, defective parts and end-of-life components is collected and reduced in size. First, the material is ground to particles of about 4–5 mm in a dry, ambient grinding step (Macro Reduction Process), followed by wet pulverisation in an aqueous medium to produce fine powder, which is then dried. Control of particle size distribution and residual moisture are critical parameters. Schuster et al. (2022) conclude that this process has the potential to return cured and semi-cured FKM waste into a material that can be reintroduced into virgin formulations with largely preserved properties. The existence of such a process using production and post-industrial waste streams is a clear **driver**. However, the need for specialised equipment, process control and separate collection of FKM waste constitutes a **barrier** to broader implementation.

Mechanical devulcanization of ground FKM can be achieved using high shearing and squeezing forces generated by a pan mill mechanochemical reactor at ambient temperature. This high-shear mechanical milling process offers several advantages over other de-crosslinking methods. It does not require chemical agents, does not generate by-products and is energy efficient due to operation at ambient temperature. These features are important **supporting factors**, as they reduce environmental and safety concerns associated with chemical devulcanization.

The partially de-crosslinked FKM (dFKM) is mixed with virgin rubber, curing agents and other additives to form blends that can be vulcanized again. Schuster et al. (2022) show that these dFKM-based vulcanizates have mechanical properties that are comparable to, or even better than, those of vulcanizates made only from virgin FKM, and their thermal stability is not significantly affected. This good compatibility between recyclate and virgin material is a **driver** for using mechanical devulcanization in practice.

At the same time, the overall process complexity, investment costs for mechanochemical reactors, and the requirement for a consistent and well-controlled FKM waste stream remain significant **barriers**. As a result, current recycling routes for FKM are more suited to pre-consumer and post-industrial waste than to heterogeneous post-consumer streams.

Examples and more details related to recycling are provided in chapter 14.1.

9.2 Specificities of fluoropolymer recycling vs other polymers

It is a common understanding that the better the waste stream is sorted, the more efficient can plastics recycling take place. Pure fractions of individual polymer types can typically be recycled in high quality, e.g. in primary recycling (see chapter 9.1.1.1). Most melt-processable fluoroplastics, such as PVDF can be recycled in a similar way to other commodity thermoplastics, that is, by re-melting through extrusion (Wahlström et al., 2021).

Recycling processes become economically feasible primarily for waste streams that are available in sufficiently large, homogeneous quantities. In the case of fluoropolymers, recycling of production scrap does occur, but recycling from industrial or commercial end-of-life applications is generally more challenging. This is partly because fluoropolymers are typically present only in very small amounts in broader waste streams reported as less than 0.01% by weight in one European assessment which makes recovery from commingled waste impractical. As a result, the most promising recycling routes are based on controlled, pre-sorted factory or processing scrap (Conversio Market & Strategy, 2023; Deloitte, 2025; Wahlström et al., 2021).

Further, for standard polymers which are used in high quantities (e.g. (PE, PP), ABS/ASA/SAN, PS, PC/ABS, PA, PVC, PMMA POM or PC) there are specific processes available in state-of-the-art recycling to separate them e.g. from WEEE or ELV shredder residues. This enables generating sufficiently pure separated polymer fractions in significant quantities which enable the economically

feasible mechanical recycling of these "target" polymers. Current recycling infrastructure seems not to include dedicated processes for the targeted separation of fluoropolymers for their recycling. However, in theory it seems possible to develop processes for the targeted separation of fluoropolymers (e.g. density-based separation or solvent-based separation; see chapter 14.2). However, it is questionable whether such separation would generate sufficient quantities of fluoropolymers enabling their reasonable recycling. In current ELV or WEEE recycling with advanced post shredder treatment, it can be assumed that the main fraction of fluoropolymers will end up in a heavy plastic fraction which is typically submitted to incineration.

Furthermore, it is essential to detect hazardous substances within waste streams to ensure their removal before recycling (Wahlström et al., 2021). The assessment of the value chain survey showed that legal uncertainty and concerns are present among relevant actors, so that hazardous waste incineration or municipal waste-to-energy combustion is often considered the more appropriate waste management option. Clear guidance on the acceptable presence of fluoropolymers in recycled material would allow for more consideration of recycling options in this regard.

When considering the impact of fluoropolymers in recycled polymers, it is possible that a certain fluoropolymer content is present in other, conventional recycled plastic, which cannot be separated by conventional methods. Since fluoropolymers are thermally and chemically stable and/or they are sometimes not melt-processable, they do not melt, or they melt only at temperatures significantly above common target polymers such as PP or PE. As a result, if fluoropolymers are not thoroughly separated from a mixed plastic fraction (e.g. WEEE or ELV SLF) for mechanical recycling it cannot be fully excluded that their presence might influence the homogeneity and quality of the target polymer recyclates, and they might cause processing issues. However, they are expected to behave mainly as an inert-high-melting filler. For WEEE and ELV, most recycled polymers are already heavily loaded with carbon black (Signoret et al., 2019) and the very low concentration from potentially remaining fluoropolymer content most likely does not affect bulk recyclate properties in systems that are already heavily loaded with other fillers. Specific defects or occasional processing issues might still be present, however, for more demanding applications. According to an expert this aspect still requires research.

Currently decreased quality of pure fluoropolymer recyclates is solved by mixing such recyclates with virgin fluoropolymer material. Different mixture rations exist for different desired quality of fluoropolymer recyclates. Such experiences could be used to discuss on tolerable fluoropolymer content in other polymer recyclates. Research is needed in this regard.

More details are provided in Appendix 4 – Expanding fluoropolymer recycling and in particular:

- possibilities of high purity sorting are elaborated in chapter 14.2.
- more details on the current separation approaches of fluoropolymers from articles are elaborated in chapter 14.3
- considerations on a potential secondary raw material market are presented in chapter 14.4

9.3 Critical raw material

Fluorspar (calcium fluoride, CaF_2) is recognised by the European Commission as a critical raw material due to its high economic importance and significant supply risk, driven by strong import dependence and limited substitution options (European Commission, 2023). Current EU fluorspar demand is largely met through imports, mainly from China, Mexico, South Africa and Vietnam, with only marginal and declining primary production within the EU[4]. As a result, the EU remains structurally reliant on external sources for its fluorine supply (SCRREEN2, 2023). Fluorspar is the main raw material that introduces fluorine into industry. It is processed into hydrogen fluoride, which is essential for the production of fluoropolymers and other fluorine-based chemicals.

[4] https://dm-publicapi.eesc.europa.eu/v1/documents/com474-2020_part1_ext_EN.docx/content

At end of life, fluoropolymers can serve as a secondary fluorine reservoir and, if fluorine is recovered and reused, may help reduce demand for primary fluorspar. In established waste-management routes such as hazardous waste incineration, fluorine in fluoropolymers is typically converted to hydrogen fluoride and then captured in scrubbing systems as inorganic fluoride salts, often calcium fluoride. These recovered fluorides are not identical to mined fluorspar in all respects, but in some cases, they can be further processed and reintroduced into parts of the fluorine value chain, including as feedstock for HF production (Aldaco et al., 2007).

9.4 Substances of concern potentially generated by recycling processes

No information could be identified confirming or excluding that substances of concern like generated PFAS in recycling processes end up in the recycled fluoropolymer, except for recycling using irradiation. This is recognised already in EU legislation. Under the POPs Regulation (EU) 2019/1021, as amended by Delegated Regulation (EU) 2020/784, a generic Unintentional Trace Contaminant (UTC) limit for PFOA and its salts in substances, mixtures, or articles is set at 0.025 mg/kg (25 ppb). For PTFE micropowders produced by ionising irradiation or thermal degradation, the same 0.025 mg/kg limit applies when those powders are placed on the market for their final use. According to an expert this limit can be met by PTFE recyclers.

Conventional plastics can contain a broad range of additives, fillers and reinforcement materials (e.g. glass or carbon fibres) (Polcher et al., 2020; Potrykus et al., 2024). Also, commercial fluoropolymers can contain such substances or materials. Several additives are considered substances of concern. These intentionally added SoCs are not generated during the recycling process, however, they are contained in EoL plastics and might be of concern therefore in the recycling stage as well. Those substances are not considered further considered in this report as they are not a consequence of recycling.

For upcycling processes, the fluoropolymers are decomposed at temperatures >600°C under inert gas atmosphere. This results in a raw gas mixture in which around 85% of the fluoropolymer input is recovered as monomers, primarily TFE and to a smaller concentration HFP. While TFE decomposes explosively and is classified as a carcinogen according to Regulation (EG) No. 1272/2008, it is also the sole monomer for PTFE and a co-polymer for FEP, PFA and ETFE. TFE production – other than due to upcycling – relies on CaF_2, which is a critical raw material without any natural resources in Europe. The remaining gaseous fraction consists of other, undesired fluorinated byproducts, which are separated from the products stream. These 15% are usually subject to hazardous waste incineration. If compounded materials are treated, inorganic fillers (e.g. glass fibers, or mineral pigments) do not volatilise but remain in the plants as a solid residue, which is managed from time to time applying specialised procedure.

An expert stated that no formation of PFAS during shredder, extrusion and granulation processes is expected as the temperature levels are usually not sufficient for such a formation.

Another expert pointed out that during PVDF recycling HF is released, requiring a proper process to avoid any release into the environment. However, dedicated PVDF recycling companies are expected to have such processes in place.

Overall, the analysis shows that while fluoropolymer recycling is technically possible across a range of primary, secondary and tertiary routes, its practical implementation remains constrained to a narrow set of use cases, primarily clean pre-consumer and post-industrial waste streams. Structural factors such as very low concentrations in post-consumer waste, integration into complex products, high purity requirements, limited end markets for recyclates, and regulatory uncertainty continue to limit broader deployment. As a result, recycling plays a secondary role compared with waste prevention, reuse of durable components and controlled end-of-life treatment. At the same time, emerging technologies for upcycling, selective recovery and improved process control, together with clearer regulatory guidance could gradually expand recycling opportunities where sufficient material quality and volumes exist. Any realistic assessment of fluoropolymer circularity therefore needs to

reflect both the technical potential and the current practical constraints, and to consider recycling as one element within a broader, hierarchy-based end-of-life strategy rather than as a stand-alone solution.

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11. Appendix 1 - Methodology

The present project focused on a number of technical questions formulated by the Fluoropolymer Group (FPG) of PlasticsEurope related to the End-of-Life stage of Fluoropolymers.

11.1 Data collection

Apart from general literature searches in academic and grey literature, data have been collected in the course of two online surveys and additional expert interviews.

11.1.1 Value chain survey

Ramboll set up the survey questionnaire shown in Appendix 2 - Value Chain survey questionnaire. The link to the Value Chain survey questionnaire accompanied by a one pager explaining the projects background was sent out by the FPG to all available contacts along the value chain of fluoropolymers. In addition, a webinar was conducted by Ramboll for the contacted experts in order to clarify questions and explain the survey in detail. Reminders were sent out by PlasticsEurope.

Overall, 213 (partially or completely completed) questionnaires were received. Thereof, 142 questionnaires contained detailed information on the specific questions. 71 questionnaires have been excluded from the assessment as they have been classified either as double submission by same respondent, questionnaire without any information (e.g. only answered with "no information" or questionnaire without any reliable information (e.g. if indicated by respondent "we do not know but assume…").

In the following the distribution among different value chain actors is shown. The respondents consist of

- **Compounder**, who mixes fluoropolymers resins like PTFE & FKM with fillers; not all fluoropolymers are compounded, irradiated or fluorinated
- **Semi-finished stock shape producer**, who processes resin into stock shapes or semi-finished articles for supplying to part producer (including etching, coating, printing or laminating)
- **Part producer,** who supplies finished part to system producer or directly for use
- **System producer**, who uses parts in a system (complex article) and supplies this system to OEM

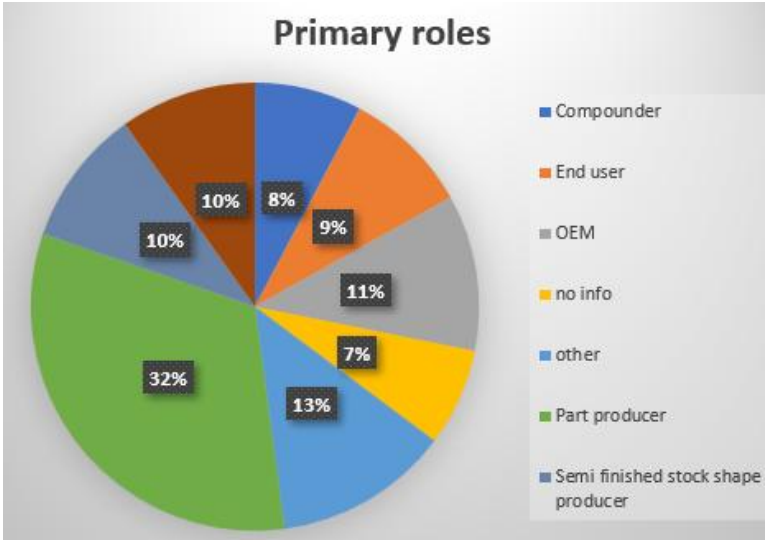

Figure 11-1: Primary roles of respondents and share of feedback per role

- **OEM**, e.g. car manufacturer, semi-conductor plant, medical equipment manufacturer etc.
- **End user**, consumers who could be common people (for consumer applications like laptops and phones or non-stick pans) or industries (e.g. CPI)

12. Appendix 2 - Value Chain survey questionnaire

Please explain briefly how you use fluoropolymers and in which articles they are finally used?

_____
_____
_____
_____
_____
_____

What proportion of your articles contains fluoropolymers and what is the estimated waste volume thereof annually?

_____
_____
_____
_____
_____
_____

Can you explain what happens to your articles when they reach the waste stage? In which waste streams do they end up?

_____
_____
_____
_____
_____
_____

How is the article that contains fluoropolymers disposed of when it becomes waste? What are the common disposal methods (e.g., landfill, incineration, recycling)?
Please explain for each article in case differences exists.

_____
_____
_____
_____
_____
_____

Please indicate a share or volumes for your individual articles that go to landfill, incineration or recycling.

_____
_____
_____
_____
_____
_____

Are there noticeable trends in the disposal methods or customer preferences related to the waste/end of life stage?

_____
_____
_____
_____
_____
_____

What are the current capabilities and limitations for separating FP from end-of-life vehicles and other articles in general?

_____
_____
_____
_____
_____
_____

What are current capabilities and limitations for separating FP from other polymers/materials in general?

_____
_____
_____
_____
_____
_____

Can the fluoropolymers used in your articles be recycled?

(1) ❑ Yes

(2) ❑ No

(3) ❑ I do not know

(4) ❑ other, please explain _____

On which criteria do you base your assessment?

_____
_____
_____
_____
_____
_____

Are the fluoropolymers in your articles actually recycled or recovered?

(1) ❍ Yes

(2) ❍ No.

(3) ❍ I do not know.

(4) ❍ others, please explain. _____

Are there regulations that hinder recycling?

(1) ❍ Yes

(2) ❍ No

(3) ❍ I do not know

(4) ❍ other, please explain _____

Are there differences for specific fluoropolymers related to recycling?

_____
_____
_____
_____
_____
_____

Which fluoropolymers are recycled from your articles?

_____
_____
_____
_____
_____
_____

Do you know if the fluoropolymer material is separated from other materials before disposal?

(1) ❑ Yes, it is separated.

(2) ❑ No, it is not separated.

(3) ❑ I do not know.

(4) ❑ other please explain _____

Are there specific challenges in recovering fluoropolymers from mixed-material articles?

_____
_____
_____
_____
_____
_____

If recycling is not possible/not done, what are the barriers preventing it (e.g., cost, technology, material properties)?

_____

Do you or your customers engage with third-party recyclers for fluoropolymer-containing articles?

_____
_____
_____
_____
_____
_____

Are there any regulations / industry standards guiding the disposal of your fluoropolymer-containing articles? if yes, which ones.

_____
_____
_____
_____
_____
_____

Are there any regulations / industry standards guiding the recycling of your fluoropolymer-containing articles?

_____
_____
_____
_____
_____
_____

Do you face challenges with EoL/waste regulations specific to fluoropolymers?

_____
_____
_____
_____
_____
_____

Are your fluoropolymer containing articles designed with recycling or reuse in mind?

(1) ❑ Yes

(2) ❑ No

(3) ❑ I do not know

(4) ❑ other, please explain _____

Are there any design features that complicate the waste handling of your articles? If yes, please explain.

_____
_____
_____
_____
_____
_____

Do you collaborate with other industries or stakeholders to improve the waste processes for fluoropolymers?

(1) ❍ Yes, please explain _____

(2) ❍ No

Do you see a future potential for FP recycling for your articles/uses (obstacles and opportunities)?

_____
_____
_____
_____
_____
_____

Can recycling of fluoropolymers create a supply of valuable secondary raw materials in your sector? Please explain reasons.

_____
_____
_____
_____
_____
_____

What are the enhanced product lifetimes that are afforded by the use of fluoropolymers in your articles? (typical lifetime with and without the use of fluoropolymers)

_____
_____
_____
_____
_____
_____

Can you indicate an estimate on the reduction of waste as a result of enhanced product durability? On which facts are those assumptions based?

_____
_____
_____
_____
_____
_____

13. Appendix 3 – Expanding fluoropolymer landfilling

13.1 Criteria and requirements for fluoropolymer waste for the different classes of landfills

Landfills for inert waste

The Landfill Directive distinguishes between certain waste that may be accepted at landfills for inert waste without testing, and others for which each batch of waste must be tested.

Only well-characterised, homogeneous mineral wastes (such as uncontaminated soil, stones, concrete, bricks, or certain ceramics and glass) can be accepted. Wastes that are mixtures - particularly if they contain organic matter, metals, plastics, or hazardous components - are not permitted. For example, mixed construction and demolition waste (EWC 17 09 04) cannot go to an inert landfill; it must be treated, sorted, and directed to a non-hazardous landfill or other recovery route. For plastics in general, and fluoropolymers in particular, also the high total organic carbon (TOC) content (acceptance thresholds for inert ≤3%) means they rarely qualify as "inert waste".

Landfills for non-hazardous waste

The Landfill Directive distinguishes between certain waste that may be accepted at landfills for non-hazardous waste without testing, and others for which each batch of waste must be tested.

Given the origin and likely characteristics of fluoropolymer waste, we expect fluoropolymer waste to be accepted at landfills for non-hazardous waste without testing, where fluoropolymer waste is part of a mixture of municipal solid waste (LOW code 20 03 01). However, such mixed municipal waste streams cannot be landfilled directly, as they are subject to pre-treatment requirements, such as sorting or mechanical–biological treatment, to reduce their volume and environmental impact before disposal. In addition, European waste policy sets the principle that the landfilling of untreated municipal solid waste should be phased out entirely in the coming years. This means that the share of fluoropolymer waste ending up in landfills as part of mixed municipal waste will gradually decline.

It is rather not expected that separately collected fluoropolymer waste is being accepted at landfills due to the waste hierarchy principles when they origin from pre-consumer waste or where they occur as fraction of larger electronics or vehicles parts since this e-waste and ELV streams typically are pretreated at specific facilities, thus the streams generated there would not be identified as waste streams which can be accepted at landfills for non-hazardous waste without testing.

However, the European Waste Catalogue (EWC), provides standardised waste codes that also cover non-hazardous plastic wastes from manufacture, formulation, supply and use (EWC 07 02 13), which is classified as non-hazardous waste. Still industrial fluoropolymer waste could be landfilled according to specific local regulations - meaning non-hazardous landfills can be used unless the waste itself or its contaminants trigger hazardous waste criteria. This means it cannot be excluded that manufacturing scrap and off-spec articles are coded under non-hazardous plastic categories and end up at non-hazardous waste landfills, following testing for specific acceptance parameters.

Composite materials containing fluoropolymer coatings or jackets, such as wire insulation or gaskets, may also enter the landfill pathway, usually as part of mixed construction and demolition wastes. Mechanical separation is very difficult or economically unfeasible. During demolition or decommissioning, there is often no straight forward way to recover the fluoropolymer fraction alone. Construction and demolition generate large, heterogeneous volumes of waste. Sorting at fine detail (e.g., extracting small fluoropolymer-coated wires or seals) is typically too labour-intensive and costly. Instead, materials are grouped into bulk fractions: concrete, wood, metals, glass, and a residual mixed fraction (EWC 17 09 04, *mixed construction and demolition waste*). Fluoropolymer-containing components that are not easily separated fall into this residual stream.

According to the principles of the European Waste Catalogue and associated guidance if a waste stream contains different materials that cannot be separated without disproportionate effort, it is to

be assigned to a mixed waste code. Thus, fluoropolymer composites from buildings, cables, seals, or cladding naturally fall under this residual category when they reach end-of-life.

However, the results of the value chain survey conducted within this project indicate a growing awareness of the importance of recyclability. Stakeholders are increasingly requesting solutions that enable the recycling of components, and recyclability is becoming a critical criterion to be addressed already at the product design stage. Examples are provided e.g. for ETFE systems in chapter 14.1.

Where non-hazardous fluoropolymer waste would be subject to testing, the waste acceptance criteria contain the following leaching limit values for fluoride content for landfills for non-hazardous waste:

Component	**Liquid/Solid = 2 l/kg**	**Liquid/Solid = 10 l/kg**	**C_0 (percolation test)**
	mg/kg dry substance	mg/kg dry substance	mg/l
Fluoride	60	150	40

The fluoride leaching is determined using the EN 12457 batch leaching test. In this test, a representative granular waste sample is mixed with deionised water at a specified liquid-to-solid ratio (commonly L/S = 2 or 10), agitated, and then the eluate is analysed for dissolved parameters including fluoride. This method measures the soluble and leachable fraction of the waste, not the total fluoride bound in the material. For fluoropolymers such as PTFE, PVDF or ETFE, the carbon-fluorine bonds are extremely stable, and the polymers are essentially insoluble under the neutral conditions of the test. As a result, they would not release significant amounts of fluoride ions into the eluate. It is therefore highly unlikely that bulk fluoropolymer articles would approach or exceed the 60 mg/kg fluoride leaching threshold.

Landfills for hazardous waste

Powders, sludges, or filter cakes generated during fluoropolymer processing present a more complex case: because these residues can contain processing aids, surfactants, or other co-contaminants, that may be classified as hazardous. In such cases, pre-treatment steps such as dewatering or solidification are often required before landfilling is permitted.

The Landfill Directive establishes that each batch of waste must be tested, and the WAC contains the following leaching limit values for fluoride content for landfills for hazardous waste:

Component	**Liquid/Solid = 2 l/kg**	**Liquid/Solid = 10 l/kg**	**C_0 (percolation test)**
	mg/kg dry substance	mg/kg dry substance	mg/l
Fluoride	200	500	120

It is important to note that, in this case, due to exceptional stability of fluoropolymer, it is not likely this parameter would be exceeded, and some portion of fluoropolymer waste could end up landfilled at landfills for hazardous waste.

From the perspective of long-term safety, it is important to distinguish between the inertness of bulk fluoropolymers and the potential mobility of other fluorinated substances that may be present in the waste stream. While PTFE or PVDF articles themselves have extremely low solubility, residues of surfactants might lead to measurable levels of PFAS in landfill leachate. For this reason, careful waste characterisation and compliance testing are indispensable before acceptance.

13.2 Safe conditions during operation of a landfill

The Landfill Directive (1999/31/EC) governs the safe operation of landfills in the European Union primarily. This framework requires that all landfills - whether for inert, non-hazardous, or hazardous waste - are designed, constructed, and operated in a way that prevents pollution of soil,

groundwater, and surface water, and minimises risks to human health. The safety conditions can be grouped into several key areas:

Location and siting criteria

All landfill sites must be chosen with strict attention to controlling potential environmental impacts. According to the Directive, a natural geological barrier is mandatory, and when this is insufficient, it must be reinforced with an engineered liner to block the spread of contaminants. For both hazardous and non-hazardous facilities, the barrier's permeability must be $k \leq 1 \times 10^{-9}$m/s. The required thickness, however, varies. For hazardous landfills, the thickness is 5 meters, for non-hazardous ones at least 1 meter.

Bottom sealing and liner systems

Both (non-hazardous and hazardous) landfill classes require a composite liner system, which consists of the geological barrier and an artificial sealing liner. This is usually a high-density polyethylene (HDPE) geomembrane. This composite barrier prevents leachate from migrating into underlying soils or aquifers. The differences for the different landfill classes are defined primarily in the required thickness and redundancy of the system.

Leachate collection and management

All hazardous and non-hazardous landfills must be equipped with leachate drainage and collection systems placed above the liner. These ensure that any leachate generated is collected, stored, and treated before discharge. The Landfill Directive prohibits the discharge of untreated leachate. Treatment usually takes place on-site (biological, chemical, and increasingly advanced technologies for PFAS removal) or off-site at wastewater treatment facilities. This condition is the same for both landfill types, although hazardous landfill leachate typically requires more intensive treatment due to its higher contaminant load.

Surface water and gas control

Both landfill types must be designed with drainage systems to prevent surface water intrusion and with collection systems for landfill gas where biodegradable waste is accepted. Since biodegradable waste is banned from hazardous landfills, gas collection is not normally relevant there, whereas it is an essential safety measure at non-hazardous landfills still receiving municipal waste.

Operational practices

During operation, waste must be deposited in a controlled manner and covered regularly to limit nuisance, odours, and emissions. Hazardous landfills require even more stringent handling, including clear separation of incompatible wastes and more intensive record-keeping.

13.3 Safe conditions after closure of a landfill

The safe management of a landfill does not end when the site is closed. The Landfill Directive (1999/31/EC) sets out a comprehensive framework to ensure that landfills, once closed, do not pose ongoing risks to the environment or human health. The post-closure phase - often referred to as aftercare - can last for decades, depending on the type of landfill and the nature of the waste accepted. During this period, engineered containment systems, environmental monitoring, and institutional controls remain essential for guaranteeing long-term safety.

Closure of a landfill must follow a plan approved by the competent authority, demonstrating how the operator will secure the site and prevent future environmental harm.

The role of the capping system for post-closure safety is a key feature. Generally, it consists of:

- A low permeability capping layer (clay or geomembrane)
- A draining layer that may drain collected rainwater
- An insulation layer

- A protective soil layer that supports vegetation

This system reduces the penetration of precipitation into the waste body (and consequently reduces leachate generation) as well as erosion.

Even after closure, the threat of leachate generation remains for decades. Operators are required to:

- Operate the leachate collection system
- Measure the volume and substance of the liquid
- Verify treatment efficacies

Uncontrolled discharge of raw leachate to the environment is not allowed. There is also a need to maintain groundwater monitoring at wells surrounding the perimeter of the landfill, so any signs of such migration can be detected promptly. They should respond and address exceedances, and corrective actions should be implemented.

At hazardous waste landfills with leachates which may be more concentrated and persistent in composition, the monitoring and treatment requirements should be more restrictive. Non-hazardous landfills that accept biodegradable waste have other issues because the quality of the leachate changes over time, and it can be necessary to adapt in real time the method of treatment.

Gas control is a vital safety feature for landfills receiving biodegradable waste. Methane and carbon dioxide, along with small amounts of volatile organic compounds, are produced through decomposition long after the landfill is closed. Gas collection systems such as wells and piping must be maintained operational, and the gas gathered must be either flared or utilized as an energy source. Surficial and perimeter probes should be monitored for methane to ensure that fugitive gases are not released that could influence nearby structures or greenhouse gas emissions. Most of the hazardous waste landfills are not permitted to take biodegradable waste, and gas control is generally not necessary at closure.

The monitoring frequency is defined in the landfill permit but generally decreases only once long-term stability is demonstrated. In many cases, monitoring is required for 30 years or more.

Even after closure, the operator remains responsible for the site until the competent authority is satisfied that the landfill no longer poses any threat. This responsibility includes funding all necessary monitoring and maintenance. The Landfill Directive does not prescribe a fixed duration for aftercare. Instead, the landfill must demonstrate through monitoring results and technical assessments that it no longer represents a risk to the environment. For non-hazardous landfills with biodegradable content, this usually requires proof that leachate generation has declined to a level compatible with natural attenuation and that gas production has ceased. For hazardous waste landfills, the criterion is that the containment system remains intact and effective over the very long term. Only when authorities are satisfied the site may be released from active aftercare.

14. Appendix 4 – Expanding fluoropolymer recycling

14.1 Examples of fluoropolymer recycling

14.1.1 PTFE and fully fluorinated thermoplastics

In 2015, Dyneon opened a pilot plant for the tertiary recycling (upcycling) of fluoropolymers in Germany. Dyneon used a pyrolysis method, in which perfluorinated fluoropolymers are decomposed, gaseous monomers are regained, cleaned first, and then fed back into production. The plant is designed to handle up to 1,000 tonnes of fluoropolymer waste annually. It enables to process waste (blocks, pellets, liner, semi-finished goods, machining waste, chips, etc.) of virgin PTFE, PFA and FEP including compound with carbon fibre, carbon or graphite (3M Dyneon, 2016). The process is suitable even when they contain mineral fillers, and is reported to recover the monomers TFE and HFP at efficiencies of approximately 90–95% (Wahlström et al., 2021).

After 2020 the plant was operated only sporadically. Currently the plant is not working, however, it is ready to operate and process 1000 t/a. The fate of the plant (e.g. dismantling the plant or continuation of fluoropolymer upcycling activities) is currently unclear. It could easily be enlarged to process higher quantities (e.g. 5,000 t/a).

Based on information from an expert interview, recycling is - above a certain capacity - economically and ecologically (resource efficiency, carbon footprint) advantageous compared to production of fluoropolymers from monomers. This is why the company InVerTec (InVerTec, 2025) is currently planning large-scale upcycling plants. Secondary raw materials from production/processing for upcycling would be available, amounting to around 8.000 t/a. Additional material for upcycling is available from selected end-of-life wastes (e.g. PTFE and PFA tube bundle heat exchangers from coal-fired power plants or different fluoropolymer wastes from green hydrogen production facilities such as membranes, seals, hoses, plates, etc.). Such waste is currently typically incinerated and thus mineralised and not recycled. With upcycling, their recycling would be possible. A critical prerequisite for the success of the upcycling process is the establishment of a circular system, in which end-of-life material is supplied by one part of the industry and reintroduced as upcycled raw material by another. According to feedback from expert interviews, Asian companies (from Japan and China) are particularly interested in the upcycling technology, in the setting up of such plants as well as the use of secondary fluoropolymer material.

Even if this technique sounds promising it needs to be considered that the regenerated monomers must be very pure in order to be reused in fluoropolymer production. TFE is very sensitive to impurities. Already small amounts of hydrogen-containing species can disturb the polymerisation. Lower-purity streams might be usable for telomerisation but not for the production of high-performance PVDF or other fluoropolymers. In addition, TFE is reactive, can decompose explosively and is classified as a carcinogen. As a result, its production, purification, storage and handling require strict safety measures. Because of its explosive behaviour, transport is difficult, so generation in an upcycling process and subsequent polymerisation preferably need to occur on the same site. Storing TFE, especially in liquefied form, is energy-intensive and increases operating costs.

14.1.2 PTFE micropowders (secondary recycling/downcycling)

A specific route for PTFE is **secondary recycling into micropowders**. In this pathway, PTFE waste including production scrap is micronized into very fine powders, which are then used as performance additives in other products (see chapter 9.1.2.1 and Box 9-2).

14.1.3 Melt-processable thermoplastics (PVDF, ETFE, FEP, PFA)

According to element9 (a company which envisages to establish processes for the upcycling recycling of fluoropolymers), based on the current discussions on PFAS, fluoropolymers and additionally on CO_2 credits, it seems imperative to expand the upcycling technology and use it on a large scale to

establish a circular economy for this class of polymers. The company intends to develop business models and waste management strategies for EoL-material based fluorochemicals, quality management for secondary raw materials as well as design and engineering of upcycling plants. Element9 is also actively promoting recycling efforts for partially fluorinated fluoropolymers such as PVDF, ETFE, as well as for other fluoropolymers and compounds and laminates of perfluorinated fluoropolymers with hydrocarbon polymers in order to use such technologies on a large scale (Element9, 2025).

As regards not fully fluorinated fluoropolymers, PVDF represents the largest market segment among these materials. An expert interview revealed that while the European production market is around 11,000 tons per year, China has rapidly scaled up to roughly 200,000 tons annually, driven primarily by demand from the e-mobility sector. Today, more than 60% of PVDF is used as a binder in lithium-ion batteries, with the remainder applied in building coatings and in ultrapure water systems for semiconductor manufacturing. For the latter, one could see a link between closures of Dyneon production sites in Germany and major industries like Intel reduce or withdraw their investments in Germany.

InVerTec has created an upcycling - different to the process explained above for fully fluorinated fluoropolymers - that converts PVDF waste into valuable products such as anhydrous hydrofluoric acid and related fluorinated compounds. These substances are essential feedstocks for producing both new fluoropolymers and key battery chemicals, including $LiPF_6$, which is critical for lithium-ion battery electrolytes. In this way, waste PVDF can re-enter the production cycle and strengthen raw material security for the battery industry.

Also, Arkema has significantly advanced its recycling capabilities for PVDF through its Virtucycle® program, supported by the integration of the Agiplast recycling centre. Arkema's process includes rigorous analysis of incoming production scrap - both pre-consumer and post-consumer materials - to adjust composition and ensure high quality. The program supports closed- or open-loop recycling models, depending on the customer's needs. The recycled PVDF, branded as Agitech™ PVDF, boasts high chemical and flame resistance, making it suitable for demanding applications such as tubing, cables, and semi-finished products. According to an expert interview the process requires specific technical experiences, and segregation is a key first step that is essential. Also, a proper control of hydrogen fluoride release needs to be ensured. Current recycling capacities are in the range of some 100 t/a but could be enlarged significantly. Similar as for InVerTec, Arkema experiences growing requests from Asian companies.

Another example of high-quality fluoropolymer recycling is the specific solvent-based separation, e.g. based on the CreaSolv® process. According to Fraunhofer IVV, the process, which involves dissolving certain polymers using tailored solvents systems, followed by removal of impurities and contaminants. However, its applicability to fluoropolymers is limited, as most fluoropolymers are resistant to dissolution in common solvents. In practice, solvent-based recycling is therefore restricted to fluoropolymers that can be selectively dissolved. In this process, the target polymer can be obtained free of other polymers and impurities and competitive with the virgin polymer (Zimmermann, 2025). The research project "LIBERATION - Solution-based liberalization and reintegration of functional battery materials from cell production rejects" funded by the German Ministry of Economy and Energy (BMWK) is dedicated to developing solvent-based processes for the liberalization and reuse of these functional battery materials on a demonstration scale. Highly selective solvents with innovative properties are being developed and binding materials are extracted in a targeted manner without changing the relevant chemical-physical or electrochemical functions of the active materials. This means that the functional materials are directly available in high-quality form for reintegration into the value chain of lithium-ion batteries or alternative high-tech applications (Accurec, 2025). One aim of the project is the recycling of the active material of the cathode which contains PVDF as a binder, including the solvent-based separation of PVDF in high quality (Zimmermann, 2025).

14.1.4 Specific approaches

A film manufacturer, who supplied ETFE panels for the Allianz Arena (a football stadium in Germany) indicates a closed loop recycling for ETFE. The manufacturer reports on its website that both ETFE offcuts and inflated panels at the end of their service life can be recovered and recycled. The reclaimed material is repurposed into valves and other small parts, which are then incorporated into the production of new ETFE systems (Vector Foiltec, 2025). According to the manufacturer, these Texlon® ETFE systems are designed to work effectively for several decades. When a structure undergoes a change in use or is dismantled, the Texlon® cladding can be carefully removed and separated into its individual components, since the system does not involve hazardous or inseparable material combinations. Nearly all these components, including the ETFE foils, are recyclable. During deconstruction, trained teams collect and package the ETFE membranes, which are then sent to recycling partners for cleaning and further processing. Like production offcuts, the recovered foils are shredded and recycled, with the material subsequently used in new Texlon® system components - such as valves, flanges, or specialised packing materials.

Box 14-1: Examples for recycling of fluoropolymers not in the scope of this project

This example refers to Tedlar®, which is a PVF film. PVF is also not considered a PFAS under the broader definition due to its chemical structure.

An expert mentioned in an interview that considering the increasing quantities of photovoltaic (PV) waste (see chapter 0), fluoropolymer specific solvent-based recycling could be a promising approach to specifically recycle fluoropolymer based backsheets from waste PV panels. However, another expert expressed while confirming the possible technology concerns about the economic considerations in this regard. Within composite materials as in the case of the backsheets the uneconomic recycling of e.g. polyamide or polyethylene often constitutes a barrier for the fluoropolymer recycling. Rubino et al. (2021) carried out a pilot micropilot-scale study in Italy to improve recycling of end-of-life photovoltaic panels, with a particular focus on the polymeric backsheet (Tedlar®) and on the recovery of valuable metals. The process built on the EU-funded Photolife project and combined mechanical pre-treatment with solvent extraction using cyclohexane, which enabled effective separation of Tedlar from EVA residues and other components. Further thermal treatment of the EVA fraction facilitated the recovery of silver and silicon from the embedded PV cells. The optimised process achieved recycling rates of 82% and recovery rates of 94%, surpassing EU regulatory targets, and crucially avoided the potentially uncontrolled release of toxic fluorinated compounds from the backsheet during thermal metal recovery. While the applicability of the recovered Tedlar was not assessed, the study demonstrated that selective backsheet separation both enhances recycling efficiency and reduces environmental risks (Rubino et al., 2021).

14.2 Possibilities for high purity sorting

Especially for achieving a circular economy for plastics, sorting waste streams into high-purity fractions is a major requirement. High-purity does not only mean separating one polymer type from another, but it also means removing additives, flame retardants, and hazardous polymers to a level that enables safe re-compounding into new products. End-of-life vehicles and waste electrical and electronic equipment are central as they generate large volumes of plastic waste with complex compositions, dark colours, and a legacy of additives. Thus, possibilities in these sectors can be considered most crucial to investigate the current possibilities for high purity sorting.

In ELV and WEEE mechanical pre-treatment is the first step consisting of dismantling, shredding, washing and size classification. Subsequently a combination of complement techniques can be used. This includes nowadays near infrared (NIR) or mid infrared (MIR) spectroscopy or to a smaller extent tribo-electrostatic separation. NIR can rapidly distinguish major resins, while MIR has become essential for dark and black plastics that NIR cannot see. While NIR and MIR benefits from a sorting step ahead of the process it is crucial for tribo-electrostatic separation ((Van Den Eynde et al., 2024).

Density based sorting still plays the major role in this regard with spectroscopic sorting or Artificial Intelligence classification models as alternative for specific applications, especially in cases in which the throughput is limited and dry sorting is preferred.

WEEE and ELV are typically separated at 1.25kg/l, 1.1 kg/l and 1.00 kg/l.

Table 14-1: Density fractions and typical polymers as described in (Van Den Eynde et al., 2024)

Density fraction	Typical polymers	Source	Subsequent steps
Float at 1.00 kg/l	unfilled polyolefins polypropylene (PP) and polyethylene (PE)	(Bill et al., 2022; Strobl et al., 2021)	Further sorting by means of NIR → pure PP and PE streams compounded into granules and blended with virgin material
Float at 1.10 kg/l **Sink at 1.00 kg/l**	filled PP and non-halogenated acrylonitrile butadiene styrene (ABS) and high impact polystyrene (HIPS)	(Bill et al., 2022)	Further sorting by means of NIR or electrostatic sorting → non halogenated ABS and HIP separated from halogenated
Float at 1.25 kg/l **Sink at 1.10 kg/l**	halogenated ABS and HIPS, in addition to polycarbonate (PC), PC/ABS, polymethyl methacrylate (PMMA), polyamide (PA), filled PP and soft polyvinyl chloride (PVC)	(Bill et al., 2022; Strobl et al., 2021)	Usually incinerated due to POPs regulation or because further sorting and recovery is usually not economically viable Alternatively co-processed in cement kilns or landfilled depending – among other factors – on the halogen content and local legislation
Sink at 1.25 kg/l (not always performed)	PVC and polyoxymethylene (POM)	(Maris et al., 2015; Strobl et al., 2021)	Most likely to be landfilled If not separately sorted managed together with previous fraction

The effectiveness of the density separation has a significant impact on how much plastic waste finally gets recycled, incinerated or landfilled.

Among WEEE plastics, the major challenge is not only polymer separation but also removing additives. Flame-retarded ABS, HIPS, and PC/ABS blends are widely used for electronic housings. Even trace amounts of BFR-laden plastics can put recycled streams over regulatory limits.

For the density separation processes, the most important parameter is the medium density, which has an impact on the purity as well as the yield of the streams that are produced. If the medium density is set too low, such as during an overly conservative separation of materials, more of the recyclables may be incinerated, or more of the waste may be landfilled when it could be incinerated. On the other hand, if the medium density is set too high, it may cause incorrect output fractions and, as an example, the concentration of some persistent organic pollutants (POPs) of a fraction intended for recycling could exceed the legal permissible concentration limit (Van Den Eynde et al., 2024).

In practise, waste companies select a medium density that deviates slightly from the values elaborated above depending on their specific waste input. It is crucial for obtaining high purity sorting to control and adapt accordingly to any waste input changes. Experiences and technological knowledge at the waste management plants is essential in this regard.

A very recent article by Van Den Eynde et al. (2024) presents results of an analysis of the effectiveness of plastic sorting processes at a large Belgium sorting company. The findings show that the efficiency of the separation process is highly sensitive to even minor changes in medium density. This means that maintaining precise control of the density throughout the entire operation is essential. Selecting appropriate target densities is equally important. For dividing the heaviest and intermediate fractions, the current reference value of 1.22 kg/l seems somewhat conservative. Literature suggests that using a value closer to 1.25 kg/l is more common and would increase the share of the intermediate fraction without pushing its chlorine content above the acceptable threshold of 1 wt%. This adjustment would also reduce the portion of material sent to landfill. In the

case of separating the lightest and intermediate fractions, a density near 1.09 kg/l ensures that the floating portion complies with present POP regulations and can be recycled. However, should these limits become stricter in the future, a lower density may be required, as elevated bromine levels are already detected at densities greater than 1.07 kg/l (Van Den Eynde et al., 2024).

Many publications and research projects focus on improving polymer sorting in order to increase recycling targets, however, fluoropolymers are not specifically considered.

In general, fluoropolymers exhibit high densities. This puts them in a different sink–float window than other polymers. In practice, density separation may be able to concentrate fluoropolymers. This is elaborated in more detail on Box 14-2.

Furthermore, research data on further separation techniques like near-infrared sorting (NIR) for fluoropolymers are not published and limited awareness and knowledge seem to be available at plants.

While separation may be feasible for large or pure fluoropolymer parts, it is far less realistic for composites or mixed plastics where fluoropolymers remain bound to other materials even after shredding. Experts confirm that current sorting technologies in conventional plants are not sufficient for such cases, highlighting a clear need for further research.

14.3 Separation of fluoropolymers from articles and materials

In many typical applications, such as in the electronics and the transport sector, fluoropolymers are contained in small quantities and in small components and the separation of fluoropolymers from WEEE or ELVs is typically difficult. Further the separation and recycling of fluoropolymers in these waste streams are not the target of current recycling activities.

Based on the feedback received, the majority of respondents was not aware if their relevant fluoropolymer part in post-consumer waste is separated before disposal. Only one participant confirmed that fluoropolymers are separated before disposal. Another made it clear that no such separation takes place. A third response did not directly address separation but described a design approach in which products are intentionally made from a single polymer type. This strategy reduces the need for sorting at the end of life, although it does not imply that fluoropolymers are actively separated when used in multi-material products or composite structures.

Overall, the findings suggest that dedicated separation of fluoropolymers is uncommon and generally not monitored. This is due to technical or practical challenges related to the use of fluoropolymers in only small quantities, small components, or difficulties related to separation (fluoropolymers are contained in small fractions and pieces in complex products, they are connected/fixed to other materials/components or used in composite materials). As a consequence, fluoropolymer components are often not easily or not reasonably possible to dismantle and or separate from other components/materials.

However, ELVs and WEEE are among the most relevant fluoropolymer containing waste streams (see chapter 0). Therefore, the following chapters elaborate first on capabilities and limitations for separating fluoropolymer from end-of-life vehicles and electronic equipment and then consider post shredder concepts jointly.

14.3.1 End of Life Vehicles

The EU’s End-of-Life Vehicles (ELV) Directive lays down clear requirements for how cars must be dismantled once they reach the end of their useful life. At the heart of the legislation is the principle that vehicles should not simply be shredded as they are; instead, they must first go through a careful depollution and dismantling process. Authorised Treatment Facilities (ATF) are responsible for removing all fluids - such as fuel, oils, and coolants - as well as hazardous components like batteries, airbags, and switches containing mercury. Certain items with high reuse or recycling value, also have to be taken out before the car is processed further. Those items often contain fluoropolymers.

The Directive also makes dismantling a cornerstone of Europe's recycling targets. By weight, at least 95% of a vehicle must be reused or recovered, and at least 85% must be reused or recycled. To help reach these ambitious goals, dismantling has to be carried out in a way that preserves the value of reusable parts and enables clean separation of materials for recycling. Vehicle manufacturers are also obliged to design their products with dismantling in mind, avoiding hazardous substances and ensuring that materials can be separated at end of life. They must also provide dismantling manuals and technical information through the International Dismantling Information System (IDIS), which guides treatment facilities on how to remove components safely and efficiently. In practice, the Directive turns dismantling into a crucial stage of the circular economy for vehicles. However, fluoropolymers are not mentioned as a recycling target.

In practise fluoropolymer parts in cars - e.g., PTFE/FKM seals, hose liners, wire/cable jackets - are rarely removed separately, they either (a) stay on metal parts and are burned off in metal melting (fumes treated), or (b) end up in the shredder "light fraction" plastics that typically go to energy recovery or landfill. In most applications, fluoropolymers only make up a very small fraction of the overall product. It is estimated that a modern automobile contains about 350 grams of fluoropolymers, with projections showing that this figure could rise to between 1 and 2 kilograms per car within several years as applications expand (Wahlström et al., 2021).

The reasoning, why fluoropolymers are not separated from ELV is most likely a combination of insufficient amount of recoverable material, non-existent European market for secondary raw material, and an economic advantage for other EoL options compared to the separate collection and recycling (see chapter 4.3).

14.3.2 WEEE and energy related equipment

Fluoropolymers also play an important role in many electronic devices because of their strong dielectric behavior and resistance to chemicals. However, their proportion within the overall product mass is usually quite small. This limited fraction, combined with the difficulty of separating different polymer components, makes recycling challenging. Established industrial recycling methods focus mainly on metals like cobalt and nickel, often relying on a combination of pyrometallurgical and hydrometallurgical techniques (Wahlström et al., 2021).

Waste from photovoltaic (PV) panels – confirmed also in an expert interview - is becoming an increasingly significant part of the WEEE stream. The backsheet layers, which often contain fluoropolymers, can either be removed at high temperatures or mechanically stripped before recycling the solar cells. However, once valuable metals such as aluminium, copper, silver, and steel have been recovered, the remaining material is usually incinerated or disposed of in landfills, largely for cost-related reasons. Similar challenges arise with other energy technologies that rely on fluoropolymers, such as fuel cells, rechargeable batteries, and related applications, which are now reaching their end of life. These products frequently incorporate critical raw materials and precious metals - like cobalt in lithium-ion batteries or platinum in fuel cells - that are typically recovered using pyrometallurgical or hydrometallurgical techniques (Wahlström et al., 2021).

14.3.3 Post shredder treatment

Waste originating from both sources (ELVs and WEEE) should be treated as separate waste streams with specific pre-treatment technologies as both waste streams are governed by two different legislations. However, while the pre-treatment lines are mostly separated, it seems that the metal fractions they generate can converge. Waste arising from the automotive and electronic sectors typically end up in metal shredding plants and are often treated jointly (Wahlström et al., 2021).

In state-of-the-art recycling, after shredding, the output streams can be subject to different levels of post shredder treatment (PST). In advanced PST, plastic-rich fractions are generated (the so called "shredder light fraction" (SLF) and the "shredder heavy fraction" (SHF)). There is a variety of processing methods for plastic-rich recyclable material stream available, including e.g. manual

dismantling and sorting, magnetic separation, electrostatic sorting, density separation in liquids, NIR-sorting or different sensor-based sorting methods (Potrykus et al., 2024). The sequence of steps applied in plastic recovery and sorting plays a decisive role in determining both the yield and the purity of mechanically recyclable thermoplastics. By dismantling suitable plastic parts early in the process, it is possible to separate them by polymer type and additive composition. This reduces the complexity of the resulting waste streams, allowing for more efficient processing, higher recovery rates, and improved recyclate quality. In contrast, when plastics from WEEE or ELVs are directly fed into post-shredder technologies (PST), they are shredded together with other materials, producing highly heterogeneous waste fractions. Separating these mixtures requires significant effort and even extended PST methods cannot achieve complete separation, which limits the potential for high-quality recycling of the plastic components (Potrykus et al., 2024).

Core technologies of applied industrial processing of plastic-rich sorting fractions are density-based and electrostatic sorting processes. Figure 14-1 shows a sequence and sorting tasks for a typical processing of a plastic-rich WEEE fraction.

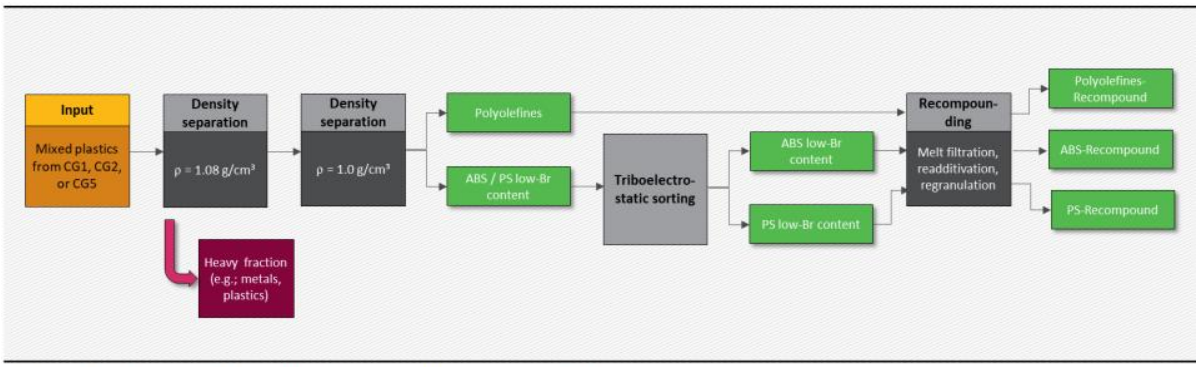

Figure 14-1: Typical processing of a plastic-rich WEEE sorting fraction in PST (source: (Potrykus et al., 2024))

Density-based sorting in swim-sink processes is state of the art in advanced WEEE or ELV post shredder treatment processes for plastic recycling. In combination with other process steps, high purities of individual target polymers can be achieved. Subsequent plastic recycling is often primary (mechanical) recycling; however, other recycling (e.g. solvent based) would be possible. The recycling of plastics from WEEE and ELVs is described in detail in (Potrykus et al., 2024).

No indication could be found that fluoropolymers are currently target polymers in established advanced PST processes. This is most likely due to technical and related economic challenges.

However, their separation would be technically feasible in theory. This is explained in the following.

Box 14-2: Theoretical considerations for separation of fluoropolymers

If fluoropolymers are present in ELV and WEEE shredder fractions they are expected to accumulate in the plastic fractions, and more specifically in the heavy plastic fractions, due to their comparatively high density (which is in the range between 1.7 and 2.2), it can be expected that fluoropolymers become (unintentionally) part of high-density plastic fractions. Such heavy fractions are typically separated from the recycling stream because they contain additives of concern (e.g. such as BFRs). They are therefore typically incinerated with the intention to destroy substances of concern (SoC) contained in them. Based on their properties, separation of fluoropolymers from other polymers would be technically possible in theory. They could, e.g. based on their high density, be separated in airstream or swim-sink processes.

Typical target polymers and other polymers contained in electrical and electronic equipment or vehicles are polyolefins (PE, PP), ABS/ASA/SAN, PS, PC/ABS, PA, PVC, PMMA POM or PC. These polymers can contain other materials/substances like mineral fillers, fibers or other additives such as flame retardants, which typically increase their density. The densities of these polymers in WEEE or ELVs including fillers, fibers and other additives range between ~0.9 and 1.6 (see

(Potrykus et al., 2024), Figure 32). The densities of typical fluoropolymers (without additives) ranges between 1.7 and 2.2 (ECTFE 1.7, PCTFE 1.7, ETFE 1.74, PVDF 1.78, FEP 2.15, PFA 2.15 and PTFE 2.17) (ptfe-machinery, 2017).

Therefore, from a plastic fraction from WEEE or ELV shredding, fluoropolymers could in theory be separated by a swim-sink process step with a density cut e.g. at 1.65. Typical target polymers and other polymers contained in WEEE and ELVs plastic fractions would end up in the light fraction (swim fraction), whereas the fluoropolymers would end up in the heavy fraction (sink fraction). With a second process step and density cut e.g. at 2.0, the "light fluoropolymers" (ECTFE, ETFE and PVDF) could be further separated from the "heavy fluoropolymers" (FEP, PFA and PTFE).

Whether, based on their properties, these fluoropolymer groups could be further separated, and by which means could be subject to further investigation. Possible means could e.g. be LIBS (laser-induced plasma spectroscopy), laser-induced fluorescence spectroscopy or specific solvent-based dissolution and separation.

This theory has been discussed with experts and while in general considered possible, some limiting factors have been mentioned as well.

While the theory above is considered possible for pure or sufficiently big fluoropolymer parts contained in the waste stream, it becomes more and more unrealistic for composite materials, for mixed polymers in which fluoropolymers are additives or for which the fluoropolymer stays with other material even after shredding. For the latter, an expert confirmed that the current sorting processes in common waste management plants are not sufficient for adequate separation. Research is needed in this regard.

14.4 Secondary raw materials

14.4.1 Potential for recycling to create a supply of valuable secondary raw materials

Stakeholders' views on the potential of fluoropolymer recycling to generate valuable secondary raw materials are strongly shaped both by the type of recycling process considered, which are primary mechanical, secondary (downcycling) or tertiary (upcycling), and by the specific polymer family, such as PTFE, other thermoplastic fluoropolymers or fluoroelastomers and composites.

In the following detailed stakeholder feedback collected within this study is summarised below, underlining the elaborations above.

Summary of stakeholder feedback

For **primary mechanical recycling**, many respondents highlighted that the niche character and low volumes of numerous fluoropolymer applications are a fundamental limitation. In many products, the fluoropolymer content is so minimal that the effort needed to identify, separate and recover it would involve complex manual work that is not commercially viable. This is particularly true where fluoropolymers are embedded in composite structures or coatings, or present only as small components.

While melt-processable thermoplastics such as PVDF, ETFE, FEP and PFA are, in principle, suitable for mechanical recycling when clean and segregated streams exist, stakeholders emphasised that such conditions are the exception rather than the rule in post-consumer waste. For PTFE, several respondents pointed out that its extremely high melt viscosity makes conventional thermoplastic recycling impossible, meaning that only very limited near closed-loop mechanical routes are realistic.

In the area of **secondary recycling or downcycling**, stakeholders acknowledged that routes such as the conversion of PTFE into micropowders for use as additives in inks, coatings, plastics or lubricants are technically feasible and already implemented in some cases. Nevertheless, many did not view these pathways as "true" circularity, since the recycled material is typically down-cycled into lower-grade or dispersive applications rather than being used again in high-value fluoropolymer articles.

By contrast, **tertiary or upcycling** were often seen as offering the greatest potential to produce high-quality secondary raw materials, albeit under specific conditions. A significant share of participants expressed conditional support for chemical recycling, emphasising that – if carried out under robust quality assurance – it can yield clean, high-grade outputs that may in some cases substitute virgin material. This was viewed as particularly relevant for PTFE and closely related polymers, which are expensive to manufacture and rely on limited and strategically sensitive raw material bases. Several respondents linked this potential to broader policy and market developments. They noted that legal frameworks such as the EU Ecodesign Directive or the EU Taxonomy Regulation could enhance the value of recycled fluoropolymers if they begin to encourage or mandate recycled content, thereby stimulating demand and supporting more robust circular business models. Secondary markets for fluoropolymers were seen as likely to emerge especially if virgin material becomes more costly or harder to source. At the same time, many stakeholders pointed to significant regulatory and sector-specific barriers. In particular, they stressed that in fields such as food contact, medical devices and drinking water applications, strict rules effectively ban the use of non-virgin materials. In these cases, even high-purity recyclates are often not permitted due to concerns over contamination, traceability and long-term performance.

14.4.2 Material composition and homogeneity of Fluoropolymers

The material composition and homogeneity of fluoropolymer (FP) recyclate fundamentally depend on the type of recycling process employed and the management of input streams. For pure PTFE (polytetrafluoroethylene) machining scrap that is well-sorted and free from contamination, the recyclate is almost entirely PTFE; however, mechanical properties such as tensile strength and elongation at break are typically reduced compared to virgin material (pro-K, 2018). Homogeneity is highest when the input stream consists of a single PTFE grade, strictly separated from other polymers and well-cleansed of lubricants or coolants, as highlighted in industry guidelines and regulatory documentation. Mixed or poorly sorted grades inevitably result in reduced uniformity and unpredictable properties, underscoring the importance of rigorous stream management.

In the case of filled fluoropolymer compounds - such as PTFE or FEP blended with glass, carbon, bronze, or pigments - the recyclate contains both the fluoropolymer matrix and its incorporated additives because existing recycling technologies cannot economically separate fillers from polymers (pro-K, 2018). This fixed composition constrains the recyclate's material properties and applicability are determined by the type and proportion of fillers. Therefore, maintaining single-compound streams is essential for consistency across batches; otherwise, heterogeneity increases, and downstream processing challenges grow.

When PTFE undergoes degradation - either by irradiation or thermal-mechanical methods - its molecular structure and material properties are significantly altered. As a result, the resulting micropowder cannot fulfil the requirements of conventional PTFE applications. However, these PTFE micropowders offer valuable performance enhancements as additives in a variety of fields. For example, they are used in non-PTFE plastics to promote lower friction and smoother processing, incorporated into lubricants to boost lubricity, added to elastomers for improved release properties, included in printing inks to make surfaces less prone to sticking or soiling, and blended into coatings and paints to enhance both non-stick behavior and ease of application (pro-K, 2018).

Multiple well-established methods are now used for primary recycling of fluorothermoplastics. In film extrusion, for example, edge trim and scrap generated during the process are quickly pelletized and returned into the production cycle. Material collected during equipment start-ups and shut-downs - although it may possess properties different from standard product - is separated as a single type, cleaned, pelletized, and then fed back into thermoplastic manufacturing. While these recycled materials cannot always meet the requirements for every application, they have become widely accepted for use in areas such as tubing and clamping solutions within architectural and power plant projects (pro-K, 2018). In an expert interview it was mentioned that after RAM extrusion, the flexural strength of PTFE typically decreases by about 30%. Because of this significant reduction, the material is generally considered unsuitable for tensile loading and is instead primarily applied in situations involving compressive loading, where its mechanical performance remains reliable.

The highest attainable homogeneity and virgin-like composition for fluoropolymer recyclate arise from chemical (tertiary) recycling. In this process, fully fluorinated fluoropolymers are depolymerized to their constituent monomers (TFE, HFP), which are then purified and repolymerized. This monomer is described by some sources as of same quality as virgin material (BOLA, 2025).