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Substance flow analysis of PFASs in Denmark

Final report

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The numbers in the first paragraph in the middle section on page 147 ('TFA related substances') were updated november 2025.

Preface

Per- and polyfluoroalkyl substances, PFASs, are a large group of around 10,000 substances which are highly persistent in the environment. PFASs have been used for more than 50 years and some of the more toxic of the substances have been restricted in Denmark and by international agreements for a number of years. Of late, a growing dataset has demonstrated the presence of the wider group of PFASs in all environmental compartments. New data demonstrates that effects of PFASs may occur at lower exposure levels than previously assessed. In consequence, PFASs have received increased attention from the public and the authorities.

A proposal for a restriction of PFASs under REACH with a wide scope was prepared by the authorities in Denmark, Germany, The Netherlands, Norway and Sweden and submitted to ECHA on 13 January 2023.

In 2024, the Government of Denmark will present a national PFAS action plan to prevent, contain and clean up PFAS contamination.

The objective of the present study is to establish an overview of the substance flow of per- and polyfluoroalkyl substances (PFASs) through Danish society by combining information on uses, releases to the environment, recovery, deposition, destruction and accumulation in society and to support the prioritization of the Danish PFAS efforts in the coming years.

The study has been followed by a Steering Committee consisting of:

- Katrine Bom, Rikke Donchil Holmberg, Mariane Hounum, Lisa Bizzaro, and Christian Lange - Ministry of Environment of Denmark, Department
- Peter Juhl Nielsen and Sehbar Khalaf - Danish Environmental Protection Agency
- Anne Krag and Carsten Lassen - COWI A/S

The study was implemented by COWI A/S during the period October to December 2023.

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Summary

In collaboration with Germany, Norway, Sweden and The Netherlands, Denmark has prepared a proposal for the restriction of the use of per- and polyfluoroalkyl substances (PFASs). The proposal was submitted to the European Chemicals Agency (ECHA) in January 2023. The PFAS restriction proposal contains detailed estimates of the consumption of PFAS, divided into a number of application areas and worst-case estimates of releases to the environment in the European Economic Area (EEA)[1].

The PFAS restriction proposals estimates of the consumption of PFASs in the EEA form the starting point for this study's estimates of the consumption of PFAS in Denmark and the possible releases to the environment from the production and use of PFAS-containing products. These estimates are supplemented with data from another restriction proposal on PFAS in firefighting foams, data on the use of PFAS in Denmark from the Product Registry, statistics on production, import and export of goods, the Danish Environmental Protection Agency's Waste Register, Danish pesticide statistics, and statistics on the consumption and releases of F-gases[2]. In order to further analyse the consumption of PFASs in production processes in Denmark, selected industry associations and individual companies were approached, but within the framework of the project and the short duration (October – December 2023), it has not been possible to carry out an in-depth analysis of the consumption of PFASs for production in Denmark.

The estimations of consumption in Denmark and the estimated releases are combined with existing measurements of PFASs by the treatment of waste and sewage in Denmark and atmospheric deposition of PFASs. Existing measurements of PFASs in the environment and by the treatment of waste and sewage are limited to a number of specific PFASs, which are used as indicators of the extent of PFAS pollution, but which do not represent the total amount of PFASs. In order to be able to convert from measured PFASs to total PFASs, in the absence of Danish data, the study has used results from foreign studies on the relationship between measured PFASs and total PFAS content.

The available knowledge is combined into a substance flow analysis, developed in accordance with the principles of the Danish Environmental Protection Agency's paradigm for mass flow analyses. The analysis follows the flow of PFASs through Danish society and the resulting releases to air, soil and surface water are estimated along with the quantities of PFASs exported with waste or destroyed by waste treatment. The further fate of the substances in the environment is not covered by the analysis, and the extent to which PFASs percolate down to the groundwater from the soil environment, surface water, contaminated land and old uncontrolled landfills has also not been estimated. Thus, the primary focus of the analysis is the releases linked to the existing uses of PFASs.

The PFAS restriction proposal applies a broad definition of PFASs, which also forms the basis for which substances were chosen for inclusion in the present study. The following three main groups are used for the analysis:

- Perfluoroalkyl acids (PFAAs) and their precursors

[1] EAA: EU, Norway, Iceland and Liechtenstein

[2] F-gases are fluorinated greenhouse gases addressed by the F-gas Regulation (Regulation (EU) No 517/2014)

    - Includes perfluoroalkyl acids (PFAA) and their precursors (including side-chain fluorinated polymers) with the exception of TFA (trifluoroacetic acid, the shortest-chain PFAA) and a number of substance groups which may be degraded to TFA
    - Encompasses other PFASs not included under the three group headings
- TFA related PFASs
    - Includes TFA, PFAS gases, and active substances in plant protection products, biocidal products and pharmaceuticals with -CF_3 moieties [3]
- Polymeric PFASs
    - Includes fluoropolymers, perfluoropolyethers and other polymeric PFASs with the exception of side-chain fluorinated polymers

This division into three groups was made in order to obtain the best overview of the flows in relation to the monitoring of PFASs that takes place in Denmark. PFAA and their precursors represent the substances that have traditionally been the focus, and which can be broken down into substances that are typically monitored in the form of $PFAS_{22}$ and $PFAS_4$, which are sums of 22 PFAAs and precursors and a subgroup of 4 of these substances, respectively. The side-chain fluorinated polymers are included in this group because the side chains may be released from the polymers over time and act as precursors for PFAAs. The shortest of the PFAAs, TFA, is monitored in Denmark on its own and has a specific drinking water quality criterion. There are a large number of fluorine gases, as well as active substances in plant protection products, biocides and pharmaceuticals which have -CF_3 moiety in their molecular structure and which can potentially be broken down into TFA, whereas they cannot be broken down into the longer-chain PFAAs, which are included in the group "PFAAs and precursors". TFA related PFASs therefore have their own group in this report. Finally, the third group is the polymeric PFASs, where the largest amounts are made up of fluoropolymers, which consist to a large extent of solid plastic or rubber materials. The borderline between the three groups is not entirely sharp; for example, TFA and PFAS gases could potentially be formed from the fluoropolymers by thermal processes.

With the method used, where quantities that are uncertainly determined at EEA level are extrapolated to Denmark, considerable uncertainty exists for all estimates. Since there is no basis for specifying uncertainty intervals in a more systematic way, a decision was made to specify all values as "best estimate". For quantities estimated on the basis of the restriction proposals alone, the "mid-point estimate" is considered to indicate the actual order of magnitude, but the actual values may be up to 3 times greater or lesser than the stated estimate. For calculated releases, the uncertainty of the individual estimates could be even greater.

A summary of the results across the three groups is shown in the table below.

Table 1. Overall summary of the results of the substance flow analysis

Gruppe	Input	Accumulation *	Disposal and emissions, t/year					
	t/year	t/yeas	Air	Soil	Surface water	Landfill	Export	Destruction
PFAAs and precursors *	300	23	2.2	4.3	1.8	6	46	209
TFA related PFASs	660	236	200	173	0,7	0	0	45
Polymeric PFASs	1,690	364	9	5	0.2	40	346	910

* Accumulation expresses the increased amount of PFASs accumulated in stocks and products in use in society. ** There is a minor imbalance between input and total output and accumulation, because it has

[3] Component of a molecule with three fluorine atoms attached to a carbon atom.

not been possible to reconcile inputs for sewage treatment calculated on the basis of the consumption of the substances, worst case emission factors used, and inputs based on measurements in the sewage.

Summary for perfluoroalkyl acids (PFAA) and their precursors

On the basis of the PFAS restriction proposal and the restriction proposal for PFASs in fire extinguishing agents, the total consumption of PFAA and their precursors in Denmark is calculated at approx. 300 t/year, of which an aggregated group of apparel, upholstered furniture, textiles, leather goods and carpets make up 57%. The largest amount is made up of side-chain fluorinated polymers used for the surface treatment of apparel and other textiles, food contact materials (apart from to cardboard and paper packaging with a restriction of PFASs in Denmark), certain building materials and medical equipment. PFAAs and their precursors are predominantly imported in finished articles; the total amount registered in the Product Register is calculated at <0.4 t/year, of which 0.3 t/year is used in paint and varnish. Of the 300 t/year, there is an accumulation in society of the order of 23 t/year. The most important disposal routes are via waste incineration plants (78% of outputs) and export (17% of outputs). Export with waste primarily consists of apparel which is assumed ultimately to end up in uncontrolled landfills or burned in open fires in recipient countries.

Emissions to air. The total emissions of PFAAs and their precursors to air are estimated at 2.2 t/year. A comparison with the total estimated atmospheric deposition over land and sea areas of 1.4 t/year indicates that the estimated emissions are of the correct order of magnitude. The total emissions from the incineration of both solid waste and sewage sludge, a subject of some discussion for a number of years, are estimated to be less than 0.1 kg/year and thus negligible in relation to the total emission to air. The destruction efficiency for PFAAs and their precursors in controlled waste incineration under Danish conditions is calculated as 99.9989% on the basis of available measurements. There is some uncertainty regarding the estimate, but it indicates that PFASs are destroyed with an efficiency that corresponds to the efficiency demonstrated for other persistent organic substances. As is mentioned in the study, regarding polymeric PFASs, there is still some uncertainty about the possible formation of fluorine gases by the combustion of polymeric PFASs.

Within the waste treatment sector, significantly higher emissions from landfills and treatment plants are estimated, which together account for an estimated emission to air of 40 kg/year. The most important types of PFASs emitted from these facilities are the volatile PFASs, such as fluorotelomer alcohols (FTOHs). Fluorotelomer alcohols are also among the PFASs emitted from products (e.g. clothing), which account for the majority of the estimated emissions to air. It should be noted that emissions from products, apart from emissions from clothing, are estimated using generic environmental release categories (ERC), which are also used for the PFAS restriction proposal, but represent worst-case emission factors. In the atmosphere, FTOH and other volatile PFAS can be oxidized to PFAA, which are more water-soluble, and subsequently delivered to the land and sea by atmospheric deposition.

Sewage and discharges to surface water. There are major uncertainties associated with the supply of PFAS to sewage and further discharges to the environment with sewage sludge and effluent from treatment plants, mainly related to the uncertainties linked to the significance of the side-chain fluorinated polymers. Apart from three studies which all concern a single specific product with side-chain fluorinated polymers (Scotchgard™ from the company 3M) in sewage sludge and agricultural land supplied with sewage sludge, no information has been identified on measurements of side-chain fluorinated polymers by sewage treatment.

On the basis of the available knowledge about consumption and emission factors, the total amount of PFASs that ends up in sewage is estimated at approx. 8.7 t/year, of which the most important sources are apparel, medical equipment (primarily production that has not been confirmed takes place in Denmark) and firefighting foams, according to the estimates. For

comparison, on the basis of measurements, it is estimated that 0.03 tonnes are added as ∑16 PFAS and the total amount of PFASs estimated on the basis of foreign studies of total extractable organic fluorine (EOF) is 0.3 t/year. A Swedish study has shown that the traditionally studied PFASs (comparable to ∑16 PFAS) only made up 1.3% of the EOF in sewage sludge, but there are no corresponding studies for sewage. Overall, the Swedish study could account for 27% of EOF by specific analysis of PFAAs and its precursors, pharmaceuticals and biocides, while the other 73% could not be determined. Direct contact with Swedish experts in the field confirms that the measurement methods used probably do not account quantitatively for polymeric PFASs in sewage and sludge. The extent to which the side-chain fluorinated polymers are included is also uncertain.

The significant difference between calculated sources and estimated quantities indicates, however, that contributions from sources to waste water may be overestimated using this method. The available data indicate that clothing and other uses of surface treatment agents are significant sources, whereas there is great uncertainty as to whether the calculated releases from medical equipment and fire-fighting foams are representative for the situation in Denmark. From 1 July 2024, it is prohibited to use PFAS-containing fire-fighting foam at fire drill sites in Denmark, whereby the inputs to soil and surface water will cease. The further fate of PFASs on fire drill sites is beyond the scope of this analysis.

The total discharges to surface water from sewage treatment plants are estimated at 0.29 t/year. For comparison, the atmospheric deposition over the waters is estimated at 0.74 t/year.

No estimates have been identified of the total inputs of PFAAs and their precursors to the inner Danish waters by ocean currents. A comparison can be made for $PFAS_4$, which illustrates the importance of discharges from treatment plants. The total estimated discharge of $PFAS_4$ (which represent a very small part of the total PFASs) to water from Danish treatment plants in 2021 is estimated in this mass flow analysis at 5.9 kg/year. For comparison, the total outflow of $PFAS_4$ from the Baltic Sea through the Danish straits in 2013 was estimated at 734 kg/year, while the inflow from the North Sea through the straits was estimated at 157 kg/year. There are no data that enable a comparison for other PFASs.

Releases to soil. Direct releases from products, especially the use of apparel and textiles, are estimated to make the largest contribution to soil. As with releases to water, the largest estimated releases to soil are made up of side-chain fluorinated polymers, but it is difficult to assess whether the releases are overestimated, as no data on the occurrence of side-chain fluorinated polymers in the environment in Denmark have been identified. Of the total releases to soil, use of sewage sludge on agricultural land (0.02 t/year) makes a small contribution compared to the total estimated atmospheric deposition over land of 0.6 t/year. The contribution of side-chain fluorinated polymers to sewage sludge may, however, be underestimated.

A single study from Canada found that the concentration of side-chain fluorinated polymers in agricultural soil that had received sewage sludge far exceeded the concentration of the traditionally measured non-polymeric PFAS. When the side-chain fluorinated polymers are released into the environment, they break down very slowly, and according to an investigation on the subject from the OECD, it is estimated that the release of the fluorinated side chains from the polymers takes place over hundreds of years.

Summary for TFA-related PFAS

The total consumption of TFA-related PFAS is estimated at 660 t/year, with the largest contribution from PFAS gases (primarily HFCs and HFOs), which made up 73% percent of total consumption, followed by PFAS active substances in pesticides (26%) and pharmaceuticals for humans (1%). There were no data available to allow a calculation of the consumption of PFAS-containing veterinary medicinal products. Compared to the calculation of the

consumption of PFAAs and their precursors, the consumption of PFAS gases and active substances in pesticides is determined with high certainty, as the calculations are based on Danish data sources. For medicinal products for humans, there is a significant uncertainty because the calculation is extrapolated on the basis of an uncertain estimate of the total consumption in the EEA.

Emissions to air. The use of PFAS gases accounts for almost 100% of the 200 t/year estimated to be released into the air. In addition, emission of PFAS gases may occur during combustion of fluoropolymers, and TFA may also be formed during thermolysis of fluoropolymers in high-temperature applications such as combustion engines and furnaces. In the absence of data, these releases have not been quantified. The total atmospheric deposition of substances (almost 100% TFA) over land and Danish waters is estimated at 24 t/year. The main source of TFA in the atmosphere is the PFAS gases, which to varying extents is broken down into TFA. The conversion to TFA of the widely used PFAS refrigerant HFC-134a, for example, is stated to be around 20%. The atmospheric lifetime of the gases of several years means that they are well mixed in the atmosphere, and the gases that lead to the deposition of TFA in Denmark could have been discharged anywhere on the globe several years ago.

Release to surface water. Municipal sewage plants are estimated to be the main source of direct discharges to surface water. The main source of TFA-related PFAS in the waste water is pharmaceuticals containing active ingredients with one or more -CF_3 moieties, and the breakdown products of the active ingredients. There is some uncertainty regarding the amounts of pharmaceuticals and metabolites in the wastewater and sludge. Based on the estimated consumption of pharmaceuticals, extrapolated from estimations of total consumption in the EEA, and the consumption of biocides, the amount discharged to treatment plants is estimated at 6.9 t/year. For comparison, the total amount based on measurements is estimated at 0.6 t/year. Since the quantities of PFAS pharmaceuticals used in Denmark are uncertainly determined, no unambiguous conclusion is drawn on as to where in this range the actual value is.

Release to soil. The most important source of discharges to soil is the use of plant protection products with active substances containing a -CF_3 component, which accounts for a release of active substances of 172 t/year. The active substances can be broken down to TFA to a certain extent, but the total amount of TFA that is formed by the final breakdown of the active substances is not known. Sewage sludge makes a minor contribution. Application of livestock manure to agricultural land can potentially spread veterinary pharmaceuticals with PFAS active substances and their metabolites. In the absence of data on the amounts of veterinary pharmaceuticals, which fall under the PFAS definition, it has not been possible to quantify this source. The total atmospheric deposition of the substances (almost 100% TFA) over land is estimated at 10.3 t/year.

Summary for polymeric PFASs

The total consumption of polymeric PFASs is calculated at 1,690 t/year, with the largest contributions from apparel and textiles, but with significant contributions from a large number of other application areas such as food contact materials and packaging, vehicles, medical equipment, and production facilities within a number of industry sectors. It has not been possible to carry out an in-depth study of the consumption of polymeric PFASs for production in Denmark, but available information from Statistics Denmark and industry organisations indicates that the total consumption of fluoropolymers for production processes in Denmark roughly corresponds to the EEA average. There is, however, not necessarily the same distribution of consumption by sector as in the EEA. The total import of the fluoropolymer PTFE in primary form, for use in production in Denmark, was 1,030 tonnes in 2021, while 22 tonnes of PFAS elastomers were imported. The total consumption of polymeric PFASs registered in the Danish Product Registry is <12 t/y, which illustrates that notification to the Registry is only obligatory if the polymers are constituents of mixtures containing substances with a harmonised

classification. There were no recorded imports of other fluoropolymers. A significant fraction of the fluoropolymers is used for surface-treatment of items which are used in a large number of sectors; for example, the food industry, the pharmaceutical industry and the wind turbine industry. The quantities of fluoropolymers in semi-finished products, used for production in Denmark, cannot be extracted from the trade statistics and no specific information has been found on this.

By determining the most likely distribution of disposal methods for the polymeric PFASs, extrapolation has been made to some extent from a study of the disposal pattern for fluoropolymers at EU level. Most types of fluoropolymers cannot be remelted and, at EU level, only a few percent are recycled. The recycled materials are primarily made up of production waste, while virtually no recycling of fluoropolymers from end-of-life products take place. No information on recycling of fluoropolymers in Denmark has been identified.

Emissions to the environment. The majority of the polymeric PFASs are fluoropolymers or fluoroelastomers, which are solid plastic and rubber materials. The total emission to the environment is estimated at 17 t/year using worst-case emission factors. Emissions are estimated to take place in the form of microplastics formed, for example, by wear and tear of surfaces coated with fluoropolymers. To put the estimate in perspective, a Danish study of emissions of microplastics calculated that the total emissions to the environment from the application areas of apparel, building materials and kitchen utensils were of the order of 0.3-1.7 t/year. The comparison indicates that 17 t/y may be an overestimate, but that the estimated quantities may not be far from the correct order of magnitude. No measurements of microplastics of fluoropolymers in waste streams or in the environment were identified that could be used to verify that releases of microplastics of fluoropolymers are taking place.

Applicability of the method

The group of PFAS that are actually used comprises hundreds and perhaps thousands of substances and they are used for a wide range of applications within all parts of society. Most of these substances do not have a harmonized classification, and it is only part of the actual consumption of PFASs in mixtures for which notification to the Product Registry is obligatory. In addition, the majority of the non-polymeric PFASs used in society are imported with articles, and there is limited knowledge about which PFASs are included in the articles and in what quantities. It is therefore assessed that an extrapolation from consumption in the EEA for most product groups leads to a more reliable estimate than what could currently be obtained from knowledge of the Danish market. In the analysis, worst-case estimates for discharges are used to a large extent, but similar to the conclusions in the PFAS restriction proposal, there is currently insufficient knowledge to refine the estimates. Despite these uncertainties, the method has proven useful for illustrating the relationship between releases from the waste stage and from the products' production and use phase, and has helped indicate where more knowledge might be needed.

Overall conclusion

The study clearly shows that waste incineration is an effective way to destroy PFASs already in circulation, and that emissions from waste and sludge incineration are insignificant compared to other sources (with the exception of certain fluorine gases when burning fluoropolymers, about which there is a lack of knowledge). For PFAAs and precursors, releases directly from the use phase are the largest sources of releases to the environment and the results indicate that it would be difficult to limit releases effectively without limiting the uses. Side-chain fluorinated polymers are estimated to be the largest contributor to emissions within the group of PFAAs and their precursors, but the available knowledge of their occurrence in waste streams and in the environment is limited. For the polymeric PFAS, the calculations indicate that they may spread as microplastics in waste streams and in the environment to a certain extent, but no studies have been identified to verify that emissions take place.

Dansk sammenfatning

Danmark har i samarbejde med Tyskland, Norge, Sverige og Holland udarbejdet et forslag til anvendelsesbegrænsning af per- og polyfluoralkylstoffer (PFAS). Forslaget blev indsendt til Det Europæiske Kemikalieagentur (ECHA) i januar 2023. PFAS begrænsningsforslaget indeholder detaljerede skøn over anvendelsen af PFAS opdelt på en lang række anvendelsesområder samt worst-case estimater over udslip til miljøet i Det Europæiske Økonomiske Samarbejdsområde (EØS)[4].

PFAS begrænsningsforslagets opgørelser af forbruget i EØS danner udgangspunkt for nærværende undersøgelses skøn over forbruget af PFAS i Danmark og de mulige udslip til miljøet knyttet til produktion og brug af PFAS-holdige produkter. Disse skøn er suppleret med data fra et andet begrænsningsforslag om PFAS i brandslukningsmidler, og data om brugen af PFAS i Danmark fra Produktregistret, Udenrigshandelsstatistikken, Miljøstyrelsens Affaldsregister, Bekæmpelsesmiddelstatistikken og opgørelser af forbrug og udslip af F-gasser[5]. For yderligere at belyse forbruget af PFAS i produktionsprocesser i Danmark er der rettet henvendelse til udvalgte brancheforeninger og enkelte virksomheder, men der har inden for projektets rammer og den korte tidsperiode (oktober – december 2023) ikke været mulighed for at foretage en dyberegående analyse af forbruget af PFAS til produktion i Danmark.

Opgørelserne af forbruget i Danmark og estimerede udslip er kombineret med data fra målinger af PFAS ved behandling af affald og spildevand i Danmark og atmosfærisk nedfald af PFAS. Eksisterende målinger af PFAS i miljøet og ved behandling af affald og spildevand er begrænset til en række specifikke PFAS, der anvendes som indikatorer for omfanget af forureningen med PFAS, men som ikke repræsenterer den samlede mængde PFAS. For at kunne omregne fra målte PFAS til total PFAS, er der i mangel på danske data anvendt resultater fra udenlandske undersøgelser af forholdet mellem målte PFAS og det samlede PFAS indhold.

Den tilgængelige viden er samlet i en massestrømsanalyse, som følger principperne i Miljøstyrelsens paradigme for massestrømsanalyser. I analysen følges flowet af PFAS gennem det danske samfund og de resulterende udledninger til luft, jord og overfladevand estimeres sammen med mængderne af PFAS, der eksporteres med affald eller destrueres ved affaldsbehandling. Den videre skæbne af stofferne i miljøet er ikke omfattet af analysen, og det er ligeledes ikke estimeret, i hvilken grad PFAS siver til grundvandet fra jordmiljøet, overfladevand, forurenede grunde og gamle ikke-kontrollerede lossepladser. Analysens primære fokus er således udledningerne knyttet til de eksisterende anvendelser af PFAS.

PFAS begrænsningsforslaget anvender en bred definition af PFAS, der også danner udgangspunkt for, hvilke stoffer, der er omfattet af nærværende undersøgelse. Stofferne er i massestrømsanalysen opdelt i tre grupper:

- Perfluoralkylsyrer (PFAA) og deres forstadier (engelsk: precursors)
    - Inkluderer perfluoralkylsyrer (PFAA) og deres forstadier (herunder sidekæde-fluorerede polymerer) med undtagelse af TFA (trifluoreddikesyre, den mest kortkædede PFAA) og en række stofgrupper, der potentielt kan nedbrydes til TFA
    - Omfatter enkelte andre stoffer, som ikke passer ind i de tre her nævnte grupper
- TFA-relaterede PFAS

[4] EØS: EU, Norge, Island og Liechtenstein

[5] F-gasser er fluorholdige drivhusgasser omfattet af F-gas forordningen (Forordning (EU) nr. 517/2014)

    - Inkluderer TFA, PFAS gasser og aktive stoffer i plantebeskyttelsesmidler, biocidmidler og farmaceutiske produkter med -CF_3 bestanddele (engelsk: moieties)
- Polymere PFAS
    - Inkluderer fluorpolymere, perfluorpolyethere og andre polymere PFAS med undtagelse af sidekæde-fluorerede polymerer

Opdelingen i grupper er foretaget, så der opnås det bedste overblik over strømmene i relation til den overvågning af PFAS, der foregår i Danmark. PFAA og deres forstadier repræsenterer de stoffer, der traditionelt har været fokus på, og som kan nedbrydes til stoffer, som der typisk moniteres for i form af $PFAS_{22}$ og $PFAS_4$, som er summer af henholdsvis 22 PFAA og forstadier samt en undergruppe på 4 af disse stoffer. De sidekæde-fluorerede polymerer er inkluderet i denne gruppe, fordi sidekæderne over tid vil kunne frigives fra polymererne og udgøre forstadier til PFAA. Den korteste PFAA, TFA, overvåges for sig selv og har et specifikt drikkevandskvalitetskriterie. Der er en lang række fluorgasser, og aktivstoffer i plantebeskyttelsesmidler, biocidmidler og lægemidler, som i molekylestrukturen har -CF_3[6] bestanddele, og som potentielt kan nedbrydes til TFA, men som ikke vil kunne nedbrydes til de længere-kædede PFAA, som er omfattet af gruppen "PFAA og forstadier". De TFA relaterede PFAS opgøres derfor som en særskilt gruppe. Endelig er der de polymere PFAS, hvor de største mængder udgøres af fluorpolymerer, som i høj grad er faste plast- eller gummimaterialer. Grænselinjen mellem de tre grupper er ikke helt skarp; eksempelvis vil der potentielt kunne dannes TFA og PFAS gasser ud fra fluorpolymererne ved termiske processer.

Med den anvendte metode, hvor mængder, der er usikkert bestemt på EØS-niveau, ekstrapoleres til Danmark, er der en ganske betydelig usikkerhed på alle estimater. Da der ikke er grundlag for på en mere systematisk måde at angive usikkerhedsintervaller, er det valgt at angive alle værdier som "bedste estimat". For mængder estimeret på grundlag af begrænsningsforslagene alene vurderes estimatet at angive den faktiske størrelsesorden, men den faktiske værdi kan meget vel være op til 3 gange større eller mindre end det angivne estimat. For beregnede udslip vil usikkerheden på de enkelte skøn kunne være endnu større.

En sammenfatning af resultaterne på tværs af de tre grupper er vist i nedenstående tabel.

Tabel 1. Overordnet sammenfatning af massestrømsanalysens resultater.

Gruppe	Input	Ophobning *	Bortskaffelse og udledninger, t/år					
	t/år	t/år	Luft	Jord	Overfladevand	Deponi	Eksport	Destruktion
PFAA og deres forstadier *	300	23	2,2	4,3	1,8	6	46	209
TFA-relaterede PFAS	660	236	200	173	0,7	0	0	45
Polymere PFAS	1.690	364	9	5	0,2	40	346	910

* Ophobning udtrykker den øgede mængde af PFAS akkumuleret i lagre og produkter i brug i samfundet.
** Der er en mindre ubalance mellem input og samlet output og ophobning, som skyldes, at det ikke har været muligt at foretage afstemning mellem tilførsler til spildevandsrensning beregnet på basis af forbruget af stofferne, anvendte worst case emissionsfaktorer og tilførsler baseret på målinger i spildevandet.

Resume for perfluoralkylsyrer (PFAA) og deres forstadier

På basis af PFAS begrænsningsforslaget og begrænsningsforslaget for PFAS i brandslukningsmidler er det samlede forbrug af PFAA og deres forstadier i Danmark opgjort til ca. 300

[6] Bestanddel af et molekyle med tre fluor-atomer knyttet til et kulstof-atom.

t/år, hvoraf en samlet gruppe bestående af beklædning, polstermøbler, tekstiler, lædervarer og tæpper udgør 57%. Den største mængde udgøres af sidekæde-fluorerede polymerer, der anvendes til overfladebehandling af tøj og andre tekstiler, fødevare-kontaktmaterialer (ud over de emballager af pap og papir, som er omfattet af en begrænsning af PFAS i Danmark), visse byggematerialer og medicinsk udstyr. PFAA og deres forstadier bliver langt overvejende importeret med færdigvarer og den samlede mængde registreret i Produktregistret er opgjort til <0.4 t/år, hvoraf 0.3 t/år anvendes i maling og lak. Af de 300 t/år sker der en mindre ophobning i samfundet i størrelsesordenen 23 t/år. De vigtigste bortskaffelsesveje er via affaldsforbrændingsanlæg (78% af outputs) og eksport (17% af outputs). Eksport med affald består primært af tøj, der efter brug antages at ende på ukontrollerede lossepladser eller afbrændes i åbne bål i modtagerlandene.

Emissioner til luft. De samlede emissioner af PFAA og deres forstadier til luft er opgjort til 2,2 t/år. En sammenligning med det estimerede atmosfæriske nedfald over land og havområder på 1.4 t/år indikerer, at de estimerede emissioner er af den rigtige størrelsesorden. De samlede emissioner fra forbrænding af såvel fast affald som spildevandsslam, som har været genstand for en del diskussion i en årrække, skønnes at være mindre end 0.1 kg/år og dermed ubetydelige i forhold til den samlede emission til luft. Destruktionseffektiviteten for PFAA og deres forstadier ved kontrolleret affaldsforbrænding under danske forhold er på basis af foreliggende målinger beregnet til 99.9989%. Der er en vis usikkerhed på estimatet, men det indikerer, at PFAS destrueres med en effektivitet, som svarer til den målte effektivitet for andre persistente organiske stoffer. Som det nævnes senere under polymere PFAS, er der dog stadig en vis usikkerhed om den mulige dannelse af fluorgasser ved forbrænding af polymere PFAS.

Inden for affaldsbehandlingssektoren estimeres væsentligt højere emissioner fra deponier og renseanlæg, som samlet tegner sig for en estimeret emission til luft på 40 kg/år. De vigtigste typer af PFAS, der udsendes fra disse anlæg, er de flygtige PFAS, som eksempelvis fluortelomer alkoholer (FTOH). Fluortelomer alkoholer er også blandt de PFAS, der udsendes fra produkter (eksempelvis tøj), og som tegner sig for størstedelen af de beregnede emissioner til luft. Det skal bemærkes, at emissioner fra produkter er estimeret ved hjælp af standard miljøudledningskategorier (ERC), der også anvendes i PFAS-begrænsningsforslaget, men repræsenterer worst-case emissionsfaktorer. I atmosfæren vil FTOH og andre flygtige PFAS kunne oxideres til PFAA, som er mere vandopløselige, og som efterfølgende vil tilføres landjorden og havet ved atmosfærisk nedfald.

Spildevand og udledninger til overfladevand. Der knytter sig store usikkerheder til tilførslen af PFAS til spildevand og de videre udledninger til miljøet med spildevandsslam og udløb fra renseanlæg. Dette hænger primært sammen med usikkerhederne knyttet til forekomsten af de sidekæde-fluorerede polymerer. Bortset fra tre undersøgelser, som alle vedrører et enkelt konkret produkt med sidekæde-fluorerede polymerer (Scotchgard^{TM} fra virksomheden 3M) i spildevandsslam og landbrugsjord tilført spildevandsslam, er der ikke fundet oplysninger om målinger af sidekæde-fluorerede polymerer ved spildevandsbehandling.

På basis af den tilgængelige viden om forbrug og worst case emissionsfaktorer er den samlede mængde PFAS, som ender i spildevand, estimeret til ca. 8,7 t/år, hvoraf de vigtigste kilder ifølge opgørelsen er tøj, medicinsk udstyr (primært produktion, som ikke er bekræftet finder sted i Danmark) og brandslukningsmidler. Til sammenligning er der på basis af målinger estimeret, at der tilføres 0.03 tons som ∑16 PFAS og den samlede mængde PFAS estimeret på basis af udenlandske undersøgelser af totalt ekstraherbart organisk fluor (EOF) er på 0.7 t/år. En svensk undersøgelse har vist, at de traditionelt undersøgte PFAS (sammenlignelige med ∑16 PFAS) kun udgjorde 1.3% af EOF i spildevandsslam, men der findes ikke tilsvarende undersøgelser for spildevand. Samlet kunne den svenske undersøgelse redegøre for 27% af EOF ved specifikke analyser af PFAA og deres forstadier, lægemidler og biocider, mens de

øvrige 73% ikke kunne bestemmes. Direkte kontakt med svenske eksperter på området bekræfter, at anvendte målemetoder sandsynligvis ikke redegør kvantitativt for polymere PFAS i spildevand og slam, og der er ligeledes usikkerhed om, i hvilket omfang de sidekæde-fluorerede polymerer er omfattet.

Den betydelige forskel mellem de opgjorte kilder og de estimerede mængder indikerer dog, at bidragene fra kilderne til spildevand med den anvendte metode kan være overestimerede. De tilgængelige data indikerer, at tøj og andre anvendelser af overfladebehandlingsmidler udgør væsentlige kilder, mens der er stor usikkerhed om, hvorvidt de beregnede udslip fra medicinsk udstyr (primært produktionen af det) og brandslukningsskum er repræsentative for situationen i Danmark. Det er fra 1. juli 2024 forbudt at bruge PFAS-holdigt brandslukningsskum på brandøvelsespladser i Danmark, hvorved tilførslerne til jord og overfladevand vil ophøre. Den videre skæbne af PFAS på brandøvelsespladser er uden for nærværende analyse.

De samlede udslip til overfladevand fra renseanlæg er estimeret til 0.29 t/år. Til sammenligning er det atmosfæriske nedfald over vand anslået til 0.74 t/år.

Der er ikke fundet opgørelser af de samlede tilførsler af PFAA og deres forstadier til de indre danske farvande med havstrømme. En sammenligning kan foretages for $PFAS_4$, der illustrerer betydningen af udledninger fra renseanlæg. Den samlede estimerede udledning af $PFAS_4$ - altså en meget lille del af de samlede PFAS - til vand fra danske renseanlæg i 2021 er i denne massestrømsanalyse estimeret til 5,9 kg/år. Til sammenligning er den samlede udstrømning af $PFAS_4$ fra Østersøen gennem de danske stræder i 2013 blevet estimeret til 734 kg/år, mens tilstrømningen fra Nordsøen gennem stræderne blev estimeret til 157 kg/år. Der er ikke data, der muliggør en sammenligning for andre PFAS.

Udslip til jord. Direkte udslip fra produkter, især anvendelse af tøj og tekstiler, estimeres at udgøre det største bidrag til jord. Ligesom for udslip til vand udgør sidekæde-fluorerede polymerer den største del af de estimerede udslip til jord, men det er vanskeligt at vurdere om udslippene er overestimeret, da der ikke er fundet opgørelser af forekomsten af de sidekæde-fluorerede polymerer i miljøet Danmark. Af de samlede udslip til jord udgør brug af spildevandsslam på landbrugsjord (0,02 t/år) et lille bidrag sammenlignet med den samlede estimerede atmosfæriske deposition over land på 0,6 t/år, men bidraget fra sidekæde-fluorerede polymerer til spildevandsslam kan være underestimeret

En enkelt undersøgelse fra Canada fandt, at koncentrationen af sidekæde-fluorerede polymerer PFAS i landbrugsjord, der havde modtaget spildevandsslam, langt oversteg koncentrationen af de traditionelt målte ikke-polymere PFAS. Når de sidekæde-fluorerede polymerer er udledt til miljøet, nedbrydes de meget langsomt, og ifølge en udredning om emnet fra OECD estimeres det, at frigivelsen af de fluorerede sidekæder fra polymererne går meget langsomt og foregår over hundreder af år.

Resume for TFA-relaterede PFAS

Det samlede forbrug af TFA-relaterede PFAS er opgjort til 660 t/år med de største bidrag fra PFAS gasser (primært HFC'er og HFO'er), som udgjorde 73% af det samlede forbrug, efterfulgt af bekæmpelsesmidler (26%) og lægemidler til mennesker (1%). Der har ikke været data tilgængelige for en opgørelse af forbruget af PFAS-holdige aktivstoffer i veterinærlægemidler. Sammenlignet med opgørelsen af forbruget af PFAA og deres forstadier, er forbruget PFAS gasser og aktivstoffer i bekæmpelsesmidler bestemt med lille usikkerhed, da opgørelserne er baserede på danske datakilder. For lægemidler til mennesker er der en betydelig usikkerhed, fordi opgørelsen er ekstrapoleret på basis af et usikkert estimat af det samlede forbrug i EØS.

Emissioner til luft. Anvendelsen af PFAS gasser står for næsten 100% af de 200 t/år, der anslås at blive udledt til luft. Derudover kan emission af PFAS-gasser finde sted ved forbrænding

af fluorpolymerer, og TFA kan endvidere dannes ved termolyse af fluorpolymerer i højtemperaturanvendelser som forbrændingsmotorer og ovne. I mangel af data er disse emissioner ikke kvantificerede. Det samlede atmosfæriske nedfald af stofferne (næsten 100% TFA) over landjorden og de danske farvande er estimeret til 24 t/år. Hovedkilden til TFA i atmosfæren er PFAS-gasserne, som i varierende omfang vil blive nedbrudt til TFA. Konverteringen til TFA af det meget anvendte PFAS kølemiddel HFC-134a er eksempelvis angivet at være omkring 20%. Gassernes atmosfæriske levetid på flere år fører til, at de er godt blandet i atmosfæren, og de gasser, der fører til deposition af TFA i Danmark, vil kunne være udledt hvor som helst på kloden for flere år siden.

Udslip til overfladevand. Kommunale renseanlæg vurderes at udgøre hovedkilden til direkte udledninger til overfladevand. Hovedkilden til TFA-relaterede PFAS i spildevandet er lægemidler og biocider, indeholdende aktivstoffer med én eller flere -CF_3-bestandele, og aktivstoffernes nedbrydningsprodukter. Der er en vis usikkerhed med hensyn til mængderne af lægemidler og metabolitter i spildevandet og slammet. Baseret på det estimerede forbrug af lægemidler ekstrapoleret fra opgørelser af samlet forbrug i EØS og forbruget af biocider er den udledte mængde til renseanlæg estimeret til 6,9 t/år. Til sammenligning er den samlede mængde baseret på målinger estimeret til 0,6 t/år. Da mængderne af lægemidler med PFAS aktivstoffer anvendt i Danmark er usikkert bestemt, kan der ikke drages en entydig konklusion om, hvor i dette spænd den faktiske værdi vil være.

Udslip til jord. Den vigtigste kilde til udledninger til jord er brugen af plantebeskyttelsesmidler med aktivstoffer indeholdende en -CF_3-bestanddel, som tegner sig for et udslip af aktivstoffer på 172 t/år. Aktivstofferne kan i et vist omfang nedbrydes til TFA, men den samlede mængde TFA, der dannes ved den endelige nedbrydning af aktivstofferne, kendes ikke. Spildevandsslam udgør et mindre bidrag. Udbringning af husdyrgødning på landbrugsjord kan potentielt sprede veterinærlægemidler med PFAS aktivstoffer og deres metabolitter. I mangel af data om anvendte mængder af veterinærlægemidler med aktivstoffer, der falder ind under PFAS-definitionen, har det ikke været muligt at opgøre denne kilde. Det samlede atmosfæriske nedfald af stofferne (næsten 100% TFA) over landjorden er estimeret til 10,3 t/år.

Resume for polymere PFAS

Det samlede forbrug af polymere PFAS er opgjort til 1.690 t/år med de største bidrag fra beklædning og tekstiler, men med væsentlige bidrag fra en lang række andre anvendelsesområder såsom fødevarekontaktmaterialer og emballage, køretøjer, medicinsk udstyr og produktionsanlæg inden for en række sektorer. Det har ikke været muligt at foretage en tilbundsgående undersøgelse af forbruget af polymere PFAS til produktion i Danmark, men tilgængelige oplysninger fra Danmark Statistik og brancheorganisationer indikerer, at det samlede forbrug af fluorpolymerer til produktionsprocesser i Danmark svarer nogenlunde til EØS gennemsnittet. Der er dog ikke nødvendigvis samme fordeling af forbruget på sektorer som i EØS. Den samlede import af fluorpolymeren PTFE, til brug for produktion i Danmark, var 1.030 tons i 2021, mens der blev importeret 22 tons PFAS elastomerer. Der var ingen registreret import af andre fluorpolymerer. Det samlede forbrug af polymere PFAS registreret i Produktregistret er <12 t/år, hvilket illustrerer, at anmeldelse til registret kun er obligatorisk, hvis polymererne indgår i blandinger, som også indeholder stoffer med en harmoniseret klassificering. En væsentlig del af fluorpolymererne anvendes til at overfladebehandle emner, som anvendes i en lang række sektorer; eksempelvis fødevareindustrien, medicinalindustrien og vindmølleindustrien. Mængden af fluorpolymerer, som indgår i halvfabrikata, der anvendes til produktion i Danmark, kan ikke uddrages af handelsstatistikken, og der er ikke fundet specifikke oplysninger om dette.

Ved fastsættelse af den mest sandsynlige fordeling af bortskaffelsesmetoder for de polymere PFAS er der i et vist omfang ekstrapoleret fra en undersøgelse af bortskaffelsesmønstret for fluorpolymerer på EU-niveau. De fleste typer af fluorpolymerer kan ikke omsmeltes, og på EU-

niveau er det kun nogle få procent, der genanvendes. De genanvendte materialer udgøres primært af produktionsaffald, mens der stort set ikke sker nogen genanvendelse af fluorpolymerer fra udtjente produkter. Der er ikke fundet oplysninger om genanvendelse af fluorpolymerer i Danmark.

Udledninger til miljøet. Størstedelen af de polymere PFAS er fluorpolymerer eller fluorelastomerer, som er faste plast- og gummimaterialer. Den samlede emission til miljøet er anslået til 17 t/år med brug af worst-case emissionsfaktorer. Udledningerne vurderes at foregå i form af mikroplast dannet eksempelvis ved slitage af overflader belagt med fluorpolymerer. For at sætte estimatet i perspektiv opgjorde en dansk undersøgelse af udledninger af mikroplast, at de samlede udledninger af mikroplast til miljøet fra anvendelsesområderne beklædning, byggematerialer og køkkenredskaber var af størrelsen 0,3-1,7 t/år. Sammenligningen indikerer, at 17 t/y formentlig er en overestimering, men at mængderne ikke nødvendigvis er helt uden for den rette størrelsesorden. Der er ikke fundet målinger af mikroplast af fluorpolymerer i affaldsstrømme eller i miljøet, som kan anvendes til at validere, at udledning af mikroplast af fluorpolymerer finder sted.

Metodens brugbarhed

Gruppen af PFAS, som faktisk anvendes, udgør hundred- og måske tusindvis af stoffer, og de bruges til en lang række anvendelser inden for alle dele af samfundet. De fleste af disse stoffer har ikke en harmoniseret klassifikation, og det er kun en del af det faktiske forbrug af PFAS i blandinger, der er omfattet af krav om anmeldelse til Produktregistret. Hertil kommer, at hovedparten af de ikke-polymere PFAS, der bruges i samfundet, importeres med artikler, og at der er meget begrænset viden om hvilke PFAS, der indgår i artiklerne og i hvilke mængder. Det vurderes derfor, at en ekstrapolation fra forbruget i EØS for de fleste produktgrupper fører til et mere sikkert estimat, end hvad der aktuelt kunne opnås ud fra kendskab til det danske marked. Der anvendes i analysen i høj grad worst-case estimater for udledninger, men i lighed med konklusionerne i PFAS begrænsningsforslaget vurderes der ikke aktuelt at være tilstrækkelig viden til at forfine estimaterne. På trods af disse usikkerheder har metoden vist sig brugbar til at belyse forholdet mellem udslip fra affaldsleddet og fra produkternes produktions- og brugsfase og belyse, hvor der kunne være brug for at få mere viden.

Overordnet konklusion

Undersøgelsen viser tydeligt at affaldsforbrænding er en effektiv måde at destruere PFAS, som allerede er i omløb, og at udslip fra affalds- og slamforbrænding er ubetydelige i forhold til andre kilder (med forbehold for visse fluorgasser ved afbrænding af fluorpolymerer, som der mangler viden om). Udslip direkte fra brugsfasen udgør for PFAA og forstadier de største kilder til udslip til miljøet, og resultaterne indikerer, at det vil være vanskeligt at begrænse udslip effektivt uden at begrænse anvendelserne. Sidekæde-fluorerede polymerer estimeres at udgøre det største bidrag til udslip inden for gruppen af PFAA og deres forstadier, men den tilgængelige viden om deres forekomst i affaldsstrømme og i miljøet er meget begrænset. For de polymere PFAS indikerer beregningerne, at de til et vist omfang vil spredes som mikroplast i affaldsstrømme og i miljøet, men der er ikke fundet undersøgelser, der kan verificere, at der sker udledninger.

1. Introduction

1.1 Objectives

The objective of the present study is to establish an overview of the substance flow of per- and polyfluoroalkyl substances (PFASs) through Danish society by combining information on uses, releases to the environment, recovery, deposition, destruction and accumulation in society.

The aim of the substance flow analysis is to support the prioritization of Danish PFAS efforts in the coming years, including the Ministry of Environment's preparation for the expected EU ban on PFASs.

1.2 Introduction to PFASs and substances within the scope

Per- and polyfluoroalkyl substances (PFASs) are a group of more than ten thousand synthetic chemicals (ECHA, 2023). The substance group is defined in a recent proposal for a restriction of the PFASs under REACH (ECHA, 2023) - referred to as the "PFAS restriction proposal" in the following - as substances that contain at least one fully fluorinated methyl ($-CF_3$) or methylene ($-CF_2-$) carbon atom, without an H/Cl/Br/I attached to it. The definition has been proposed by the OECD (OECD 2021) which has revised a previously applied definition extending the scope to include more substance groups. With the extended scope, active substances in pesticides with an aromatic ring and a $-CF_3$ moiety, for example, were included in the PFAS definition. Over the years, the OECD has compiled a number of lists of known PFASs. The most recent list is from 2018 and includes 4,730 individually identified substances (OECD, 2018).

The definition of PFASs is based on chemical structure; hazardous properties or risks are not part of the definition. The substance scope of the PFAS restriction proposal is, however, in addition concern-based, as it intends to cover only PFASs that are very persistent, with the aim to address the concerns associated with the persistent nature of these substances. Generally, PFASs are either very persistent themselves or will ultimately degrade to very persistent degradation products. There are, however, a few specific fully degradable PFAS subgroups with combinations of key structural elements for which it could be expected that they will ultimately mineralize in the environment. Substances that only contain the following structural elements are excluded from the scope of the PFAS restriction proposal:

CF_3-X or X-CF_2-X',

where X = -OR or -NRR' and X' = methyl ($-CH_3$), methylene ($-CH_2-$), an aromatic group, a carbonyl group (-C(O)-), -OR'', -SR'' or -NR''R'''; and where R/R'/R''/R''' is a hydrogen (-H), methyl ($-CH_3$), methylene ($-CH_2-$), an aromatic group or a carbonyl group (-C(O)-).

These substances are also excluded from the current study. For a detailed description of substances within and outside the scope, reference is made to the description in the PFAS restriction proposal. In the following, a brief description of the substance groups is provided.

As specified in the PFAS restriction proposal, PFASs form a broad group of substances, including volatile as well as non-volatile PFASs, anionic, cationic, zwitterionic and non-ionic substances, polymers of different kinds as well as non-polymers, amphoteric liquids (surfactants), etc., with various chain-lengths and degree of fluorination.

All through this report, abbreviations are used for the substances and substance groups. The abbreviations are explained in Appendix 1. Other abbreviations used in the report are explained in Appendix 2.

The PFAS restriction proposal distinguishes between four overall groups of PFASs:

- Perfluoroalkyl acids (PFAAs) and PFAA precursors
- Fluorinated gases
- Polymeric PFASs
- Other PFASs

An overview of groups of PFASs is provided in Table 2.

In the PFAS restriction proposal, the quantitative assessments of consumption and emissions are divided into the first three groups. For the groups of “other PFASs” very limited quantitative information is provided for a few application areas, and the available information indicates that the “other PFASs” account only for a very small part of the total tonnage. In the absence of specific information on consumption and emissions of the “other PFASs” group, the other PFASs are included in the group of perfluoroalkyl acids (PFAAs) and their precursors.

The following three main groups are used for this substance flow analysis:

- Perfluoroalkyl acids (PFAAs) and their precursors
    - Includes perfluoroalkyl acids (PFAA) and their precursors (including side-chain fluorinated polymers) with the exception of TFA (trifluoroacetic acid, the shortest-chain PFAA) and its most important precursors
    - Encompasses other PFASs not included elsewhere under the three group headings
    -
- TFA related PFASs
    - Includes TFA, PFAS gases, and active substances in plant protection products, biocidal products and pharmaceuticals with -CF_3 moieties
- Polymeric PFASs
    - Includes fluoropolymers, perfluoropolyethers and other polymeric PFASs with the exception of side-chain fluorinated polymers

The division into the three groups has been made in order to obtain the best overview of the flows in relation to the monitoring of PFASs that takes place in Denmark. PFAA and their precursors represent the substances that have traditionally been the focus and which can be broken down into substances that are typically monitored in the form of $PFAS_{22}$ or $PFAS_4$, which are sums of 22 PFAAs and precursors and a subgroup of 4 of these substances (further described in section 1.3.3). The side-chain fluorinated polymers are included in this group because the side chains may be released from the polymers over time and act as precursors for PFAAs. The shortest of the PFAAs, TFA, is traditionally monitored on its own in Denmark and has a specific drinking water quality criterion. It occurs in much higher concentrations, for example in rainwater, and is therefore calculated separately. There is a large number of fluorinated gases, as well as active substances in plant protection products, biocidal products and pharmaceuticals which have a -CF_3 moiety in their molecular structure and which can potentially be broken down to TFA, whereas they cannot be broken down into the longer-chain PFAAs, which are covered by the group "PFAA and their precursors”. Finally, the third group is the polymeric PFASs, where the largest amounts are made up of fluoropolymers, which are solid plastic or rubber materials to a large extent. The borderline between the three groups is not entirely sharp; for example, TFA and PFAS gases could potentially be formed from the

fluoropolymers by thermal processes, but the available data have not enabled a quantification of this formation.

Table 2. Overview of groups of PFASs (Based on ECHA, 2023 and Buck et al., 2011)

Non-polymers	Polymers
Perfluoroalkyl substances Compounds for which all hydrogen atoms on all carbon atoms (except for carbon atoms associated with functional groups) have been replaced by fluorine atoms, such as: • Perfluoroalkyl acids **(PFAA)** - Perfluoroalkyl carboxylic acids (PFCAs) - Perfluoroalkane sulfonic acids (PFSAs) • PFAA precursors such as: - Perfluoroalkane sulfonamides (FASAs) - Perfluoroalkyl iodides (PFAIs)	**Side-chain fluorinated polymers** Non-fluorinated polymer backbone of variable composition with polyfluorinated side chains, such as: • Fluorinated acrylate and methacrylate polymers • Fluorinated urethane polymers • Fluorinated oxetane polymers • Fluorinated siloxanes polymers
Polyfluoroalkyl substances Compounds for which all hydrogen atoms on at least one (but not all) carbon atoms have been replaced by fluorine atoms, such as: • n:2 Fluorotelomer alcohols (n:2 FTOHs) • n:2 Fluorotelomer carboxylic acids (n:2 FTCAs) • Polyfluoroalkyl phosphoric acid diesters (diPAPs)	**Fluoropolymers** Carbon-only polymer backbone with fluorine atoms directly attached, such as: • Polytetrafluoroethylene (PTFE) • Polyvinylidene fluoride (PVDF) • Fluoroelastomer (FKM)
PFAS gases Compounds such as: • Hydrofluorocarbons (HFCs) • Perfluorocarbons (PFCs) • Hydrofluoroethers (HFEs)	**Perfluoropolyethers** Carbon and oxygen (ether) polymer backbone with fluorine atoms directly attached to carbon atoms
Other non-polymeric PFASs A number of PFASs in various groups such as: • Active substances in plant protection products, biocidal products and pharmaceuticals with -CF_3 moieties • Other side-chain fluorinated aromatics • Perfluoroalkanes (non-gaseous) • Perfluoroalkyl-tert-amines	

1.2.1 Perfluoroalkyl acids (PFAAs) and PFAA precursors

For the purpose of this study, this group includes the perfluoroalkyl acids (PFAAs) and precursors of PFAAs, including side-chain fluorinated polymers. It excludes F-gases which may also act as PFAA precursors but are addressed separately.

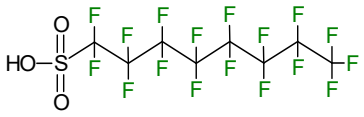
The non-polymeric PFASs comprise a range of diverse molecules and include, among others, perfluoroalkyl carboxylic acids (PFCAs, e.g. PFOA), perfluoroalkane sulfonic acids (PFSAs, e.g. PFOS and PFHxS), fluorotelomer-based compounds (e.g. 6:2 FTS), perfluoroalkane sulfonamides (FASAs, e.g. PFOSA), and perfluorotrialkylamines and per- and polyfluoroalkyl ether compounds, such as perfluoroalkyl ether carboxylic acids (PFECAs).

The perfluoroalkyl acids (PFAAs) consist of a large group of compounds consisting of a hydrophobic fully fluorinated alkyl chain of varying length (typically 4 to 16 carbon atoms) and a hydrophilic end group, $F(CF_2)_n$-R. [7]

The use of some of the PFCAs and PFSAs has been the main focal point for regulatory actions within the EU. PFOS, PFOA, PFHxS, their salts and related substances are currently restricted by the EU POPs Regulation (Regulation (EU) No 2019/1021). The C9-C14 PFCAs, their salts and related substances[8] are restricted under REACH entry 68 (the restriction is further described in section 1.3.). For many purposes, the regulated PFASs have been replaced by short-chain derivatives. The PFAS restriction proposal addresses all PFASs within the scope, independent of chain-length.

Perfluoroalkyl substances. Within the group of perfluoroalkyl substances, PFCAs and PFSAs (collectively referred to as perfluoroalkyl acids, PFAAs) are the most well described and typically account for the majority of substances measured by regular monitoring. The presence of the substances in the environment may be caused by intentional use of the substances (today or in the past) or degradation of precursors used in the past.

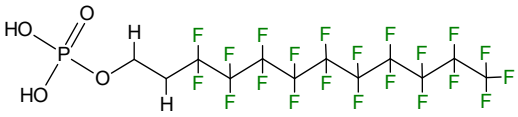
Perfluorooctane sulfonic acid (PFOS) is the most prominent of the perfluoroalkane sulfonic acids (PFCAs). PFOS has a linear perfluoroalkyl carbon chain of 8 atoms and a sulfonic acid functional group. In general for the PFAAs, the perfluorinated moiety is stable and the PFASs are generally not degraded to substances with a shorter perfluorinated chain length (i.e., C8 PFASs are not degraded to a C4 PFAS).



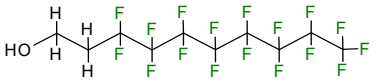
Perfluorooctane sulfonic acid (PFOS)

Polyfluorinated substances. The main product group of polyfluoroalkyl substances is comprised of the fluorotelomers. Fluorotelomers have non-fluorine-substituted hydrogen atoms (a CH_2-CH_2 group) in between the perfluorinated carbon chain and the functional group. Fluorotelomers are produced with a variety of functional groups, including alcohols, sulfonamides, sulfonamidoethyl acrylates and methacrylates, and sulfonamido acetic acids.

To name the fluorotelomers, a notation is used indicating the length of the perfluorinated carbon chain and the length of the chain with non-substituted hydrogen atoms. Below is a 10:2 fluorotelomer phosphate monoester (10:2 monoPAP) with 10 fully fluorinated carbon atoms and 2 non-fluorine-substituted atoms and an 8:2 fluortelomer alcohol (8:2 FTOH).



10:2 monoPAP



8:2 FTOH

[7] Hydrophilic = attracted to and dissolved in water, oil repelling; Hydrophobic = water repelling, prefer non-polar solvents.

[8] "Related substances" are used in regulatory contexts - The term is used interchangeably with the term precursors.

Fluorotelomers may be precursors of perfluoroalkyl carboxylates through degradation. The 10:2 fluorotelomer phosphate monoester shown above may therefore be degraded to C10 perfluoroalkyl carboxylate.

As noted in the PFAS restriction proposal, the polyfluoroalkyl acids and most of the other PFASs are not necessarily all direct precursors to PFAAs in the short term, but ultimately, somewhere in their life-cycle, they will be able to form PFAAs.

Neutral vs. ionic PFAS. Neutral PFASs such as FTOHs, FOSA and FOSE are recognized as volatile precursors and are dominant among the PFAAs and their precursors as regards emissions, e.g., from landfills, sewage treatment plants and some products. Ionic PFASs include the non-volatile PFCAs and PFSAs. Both ionic and neutral PFASs are present in the atmosphere, but the concentrations of neutral PFASs are usually much higher than those of ionic PFAS. However, the neutral PFASs may give rise to gas-phase PFCAs via OH-initiated degradation.

Main applications of the non-polymeric PFAS. A major application area for non-polymeric PFASs is the manufacture of other non-polymeric PFASs and side-chain fluorinated polymers. As regards the application of non-polymeric PFASs in final products, the main application areas are PFAS polymerisation processing aids, e.g. in plastics and rubber production; fluorosurfactants as wetting/levelling agents, e.g. in coating, paints and adhesives; surfactants in metal surface treatment, and in firefighting foams. Furthermore, the non-polymeric PFASs are used in packaging and rubber production and as a solvent in lubricants. According to the PFAS restriction proposal, non-polymeric PFASs are used in the production of side-chain fluorinated polymers used in TULAC applications, but are not themselves actually present in the TULAC final product other than as impurities.

A particular application area for the non-polymeric PFASs is fire-fighting foams. The specific restriction proposal for firefighting foams lists 63 PFASs which have been, or are currently, used in firefighting foams (ECHA, 2022). The substances include PFSAs (perfluoroalkane sulfonic acids, e.g. PFBS and PFHxS) and PFCAs (PFCAs e.g. PFBA and PFOA), derivatives of PFSAs (e.g. PFOSA, and MeFOSE), fluorotelomers (e.g. 4:2 FTS and 10:2 FTUCA), and a few other substances. The foams typically include a mixture of substances with varying chain lengths. According to the restriction proposal for fire-fighting foams (ECHA, 2022), quoting industry sources, all PFAS-containing foams produced today are based on C6-chemistry, and PFASs based on <C6-chemistry have never been used as an active ingredient for firefighting foams, as the chemistry is not suitable. However, they may be present as unintended by-products of the synthesis process. According to ECHA (2022), the EU use of PFAS-containing firefighting foams accounts for an annual consumption of around 480-560 tonnes of fluorosurfactants per year.

Side-chain fluorinated polymers. Among other uses, the fluorotelomers and other polyfluorinated substances are used to produce side-chain fluorinated polymers. The side-chain fluorinated polymers chemically belong to polymeric PFASs, but the tonnages are allocated to the group of PFAAs and PFAA precursors in this study, as was done in the PFAS restriction proposal. The side-chain fluorinated polymers consist of a carbon backbone with various polyfluorinated side chains. Side-chain fluorinated polymers are considered potential PFAA precursors. During their lifetime, the side-chains can be released mostly as telomeric PFASs, (e.g. fluorotelomer alcohols) which in turn can degrade further into PFCAs.

The actual polymers produced are often complex structures with different types of side chains, and chains of different chain length, in order to obtain the desired properties. The polymer shown to the left in the figure below has a fluorotelomer-derived perfluoroalkyl acrylate side chain to provide water and oil repellence and soil release, and a non-fluorinated alkyl acrylate

for film forming softness. Furthermore, the polymer has crosslinking monomers to provide durability. When applied e.g., on the surface of outdoor textiles, the polymers form a two-dimensional network through crosslinking, whereby the side chains protrude from the surface. For the fluorotelomer-derived urethane polymer to the right, the break of the hydrocarbon backbone and break of the side-chains by hydrolysis is illustrated.

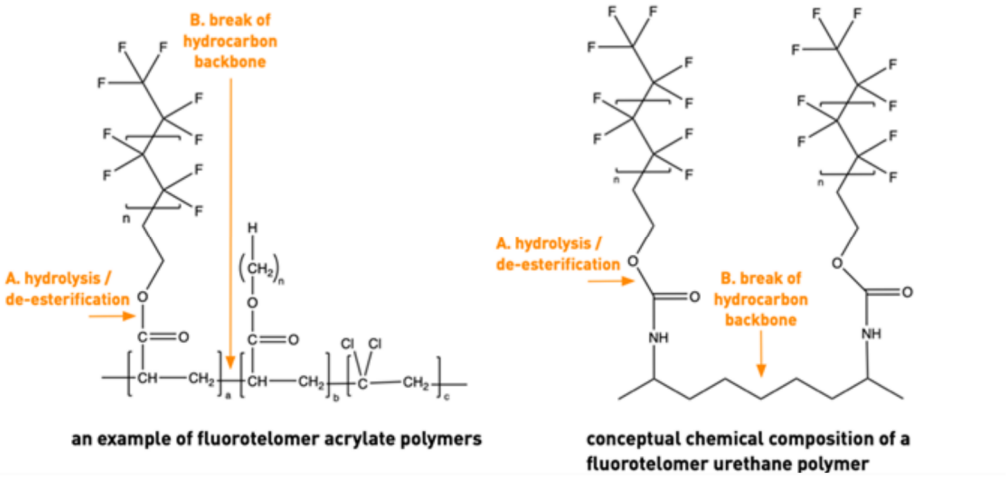
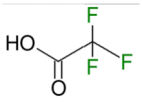


Figure 1. Polymer structure of fluorotelomer acrylate polymer and fluorotelomer (reproduced from OECD, 2022).

Side-chain fluorinated polymers are used in a broad range of applications. The main applications of the fluorinated side-chains impart water and dirt repellence to textiles, upholstery, leather, apparel, carpets (collectively referred to as TULAC), masonry, and filtration and separation media. The total volume of these polymers placed on the EU market is estimated, with high uncertainty, at 400-4,500 t/y in the PFAS restriction proposal (ECHA, 2023). The main application area is TULAC and the use in final products within this application area is estimated at 2,430 - 14,236 t/y in the PFAS restriction proposal.

1.2.2 TFA related PFASs

The PFAS restriction proposal distinguishes among three groups of PFASs, of which one is the fluorinated gases. The gases are generally small molecules, as illustrated for HFC-134a below. Their complete degradation usually yields hydrofluoric acid (HF) and, for many fluorinated gases, also trifluoroacetic acid (TFA).



Trifluoroacetic acid (TFA)

Some substances contain only a single -CF_3 group attached to carbon, and because of their structure, they are potential precursors to TFA, which is the perfluoroalkyl carboxylic acid (PFCA) with the shortest chain-length (C2). To this subgroup belong, amongst others, some fluorinated gases and active substances in biocidal products, plant protection products and pharmaceuticals containing a -CF_3 group. The three latter groups are excluded from the scope of the PFAS restriction proposal as they are already regulated elsewhere, but are within the scope of this study. These substances cannot be degraded to the traditionally monitored short- and long-chain PFAAs and, with the aim of providing a more useful overview, these substances are grouped together under the term “TFA related PFASs”. The substances have the potential to degrade to TFA (and some of them also to C3 substances), but for many of the substances it is not certain whether TFA is formed from their degradation, or to what extent this might be the case. Furthermore, thermal degradation of some fluoropolymers at certain

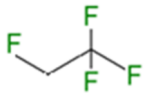
temperatures may form TFA as well as some of the substances included in the group of "PFAAs and other PFASs". The aim here is not to present a comprehensive overview of all TFA precursors, but to better provide for an overview of groups of substances, as "TFA related PFASs" quantities exceed the "PFAAs and other PFASs" with regard to atmospheric deposition and emission to air.

TFA is one of the ultrashort-chain PFASs that have received more attention in recent years. Others are mainly perfluoropropionic acid (PFPrA), trifluoromethanesulfonic acid (TFMS), perfluoroethanesulfonic acid (PFEtS) and perfluoropropane sulfonic acid (PFPrS). The latter four substances are included under "PFAAs and other PFASs" in this study, as only limited data on these substances are available.

Fluorinated gases. As the applied definition of PFASs includes substances with only one fully fluorinated carbon atom, several small, fluorinated molecules that are gases are covered. Some of these fluorinated gases are well-known heat transfer agents used in freezers, heat pumps, air-conditioning and other applications. Some of the fluorinated gases, such as the hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and hydrofluoroethers (HFEs), are addressed in the EU by the F-gas Regulation (Regulation (EU) No 517/2014). However, there are some differences in the scope of the F-gas Regulation and the PFAS restriction proposal as some substances addressed by the F-gas Regulation are not PFAS, whereas some PFAS gases are not covered by the F-gas Regulation. This situation is further described in section 2.2.15 on application of fluorinated gases.

The gases are generally small molecules as illustrated for HFC-134a below.

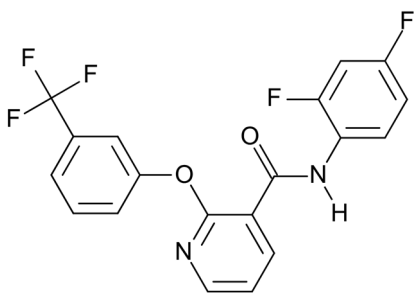
HFC-134a (1,1,1,2-Tetrafluoroethane, CAS No 811-97-2)



Some volatile PFASs, such as the fluorotelomer alcohols (FTOHs), are not included under the fluorinated gases, but rather under PFAAs and PFAA precursors. The total volume of fluorinated gases placed on the EU market in 2020 is estimated at 5,800 - 9,300 t/y (ECHA, 2023).

Active substances in plant protection products, biocidal products and pharmaceuticals. Active substances in plant protection products, biocidal products and medicinal products are considered as being somewhat different chemically from other PFAS subgroups (ECHA, 2023). Generally, these active substances are characterized by the presence of one or more -CF_3 group(s) in their molecular structure that are mostly aromatics. Introducing the -CF_3 group in the molecular structure of biologically active substances could alter specific properties, such as stability and lipophilicity. TFA is one of the possible major metabolites/degradation products for these types of substances. As most of the PFAS active substances in plant protection products, biocidal products and pharmaceuticals are potential precursors to TFA, the active substances in plant protection products and biocidal products are included in the overall group of TFA related substances in this study. An example of a PFAS active substance used in plant protection products, Diflufenican, is illustrated below.

Diflufenican (N-(2,4-difluorophenyl)-2-[3-(trifluoromethyl)phenoxy]-3-pyridinecarboxamide, CAS No 83164-33-4)



1.2.3 Polymeric PFASs

According to the PFAS restriction proposal, the polymeric PFAS group includes:

- Fluoropolymers (polymers consisting of a polymeric fluorinated carbon backbone),
- side-chain fluorinated polymers (polymers consisting of non-fluorinated polymer backbones with per- or polyfluoroalkyl/alkyl ether side-chains attached, and
- perfluoropolyethers (PFPEs; ether polymer backbone with F atoms directly attached).

As indicated above, side-chain fluorinated polymers are included in the group of Perfluoroalkyl acids (PFAAs) and PFAA precursors in the restriction proposal and in this study, because the side-chains may act as PFAA precursors. The side-chain fluorinated polymers, furthermore, are used for different purposes than other polymers, as these polymers are mainly used to provide water and dirt repellence to surfaces, whereas the fluoropolymers and perfluoropolyethers have very different application patterns.

Fluoropolymers. Fluoropolymers are a family of high-performance plastics characterized by their strong carbon-fluorine (C-F) bonds. Examples are the much-used PTFE (polytetrafluoroethylene), PVDF (polyvinylidene fluoride), FEP (fluorinated ethylene-propylene), and FKM (fluoroelastomer). The fluoropolymers accounting for the highest shares of the 40,000 tonnes of fluoropolymers converted into products by EU converters in 2020 were PTFE (56%), PVDF (12%), FEP (8%) and FKM (8%) (Conversio, 2022). The PFAS restriction proposal indicates the total EEA production volume in 2019 at 49,000 t/y.

The use of fluoropolymers by application area is described in the various subsections of section 2.2. An overview of the fluoropolymer market by component across the application areas is provided in Figure 2 below. The fluoropolymers are mainly used for solid parts of “plastics” such as tubes, liners, film, etc., while 3% are used as lubricants and greases.

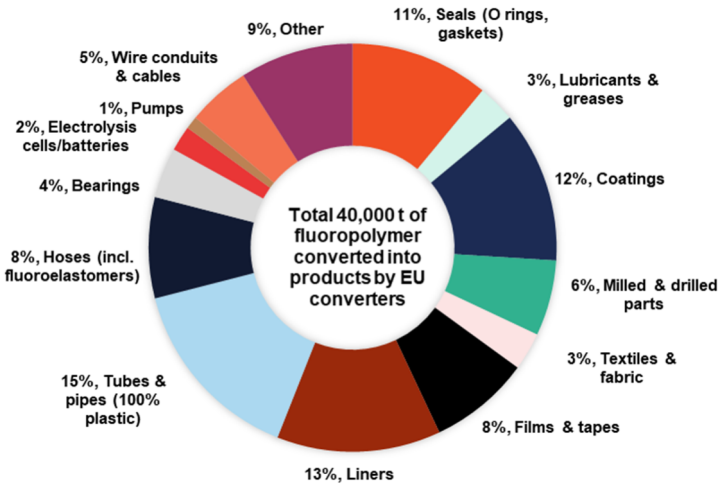


Figure 2. European fluoropolymer market by applications in 2020 (redrawn from Conversio, 2022)

Perfluoropolyethers (PFPE). Perfluoropolyethers (PFPE) comprise a type of synthetic liquid polymer lubricant used in specific industrial sectors, as well as in certain consumer applications related to surface protection. The total volume used in the EEA is not reported, but the PFAS restriction proposal estimates the following volumes for some of the applications areas (volumes are not indicated for all areas): TULAC (786 - 1,683 t/y), electronics and semiconductor industry (9 - 552 t/y), the energy sector (2 - 3 t/y) and lubricants (300-800 t/y).

1.2.4 Other PFASs

The PFAS restriction proposal lists a number of other PFASs:

- **Side-chain fluorinated aromatics**. The PFAS restriction proposal does not include information on applications or quantities used.
- **Perfluoroalkanes (non-gaseous).** One of the main PFASs use in ski waxes. Specific information on quantities is not provided in the restriction proposal, but the tonnage of all PFASs for ski wax in the EEA is indicated at 1.6 t/y.
- **Perfluoroalkyl-tert-amines**. The PFAS restriction proposal does not include information on applications or quantities used.
- **Perfluoroalkylethers**. The PFAS restriction proposal indicates the application area to be adhesives, coating and lubricant, but does not provide any estimates of quantities.
- **Others**. No further details of "others" are provided in the PFAS restriction proposal.

No quantities for the other listed PFASs are specifically provided in the PFAS restriction proposal, so it is assumed that the total quantities are very small. For three of the application areas (consumer mixtures, cosmetics, and ski wax), the PFAS restriction proposal does not indicate the split between the overall groups; PFAAs and precursors may account for a part of the indicated tonnage. These applications, however, represent about 0.01% altogether of the total PFAS tonnage. For simplicity, the total tonnage for these application areas (approximately 60 t/y) is allocated to the group "PFAAs and PFAA precursors".

1.3 Restrictions and quality criteria

1.3.1 Restrictions on the use of PFASs at EU level

Restrictions on the use of the substances at EU level, as well as restriction proposals currently under evaluation, are listed in Table 3.

The use of the substances is restricted in the EU by two main Regulations: The POPs Regulation (Regulation (EU) 2019/1021), which transposes the requirements of the Stockholm Convention into EU legislation, and REACH (Regulation (EC 1907/2006)), under which a number of restrictions are listed in Annex XVII.

The substances restricted so far are all long-chained PFAAs and related long-chain PFAA precursor substances that may be degraded to the listed long-chained PFAAs. The restricted substances also include side-chain fluorinated polymers that contain the moieties in the side-chains that may degrade into the restricted substances. Three proposed restrictions, still under evaluation, have a broader scope and include short-chain PFASs as well. The restricted substance groups include an extensive list of PFAS; for example, 173 substances are listed on ECHA's website as being members of the restricted group "Perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds".

The use of polymeric PFASs and fluorinated gases is generally not restricted thus far, with the exception of the above-mentioned side-chain fluorinated polymers.

PFAS active substances in plant protection products, biocidal products, medicinal products and veterinary medicinal products are regulated by specific legislation which restricts substances that are not approved.

Table 3. Restrictions of the use of the substances at EU level. As regards exemptions, reference is made to the original legislation.

Substances	CAS No (as indicated in the legislation)	REACH Annex XVII	POPs Regulation
Perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds 'Perfluorooctanoic acid (PFOA), its salts and PFOA-related compounds' means the following: (i) perfluorooctanoic acid, including any of its branched isomers; (ii) its salts; (iii) PFOA-related compounds which, for the purposes of the Stockholm Convention, are any substances that degrade to PFOA, including any substances (including salts and polymers) having a linear or branched perfluoroheptyl group with the moiety $(C_7F_{15})C$ as one of the structural elements.	335-67-1, and others [173 group members listed at ECHA's website][9]		X
Perfluorooctane sulfonic acid and its derivatives (PFOS) $C_8F_{17}SO_2X$ (X = OH, Metal salt (O-M+), halide, amide, and other derivatives including polymers)	1763-23-1 2795-39-3 29457-72-5 29081-56-9 70225-14-8 56773-42-3 251099-16-8 4151-50-2 31506-32-8 1691-99-2 24448-09-7 307-35-7 and others		X
"Perfluorohexane sulfonic acid (PFHxS), its salts and PFHxS-related compounds" means the following: (i) perfluorohexane sulfonic acid, including any of its branched isomers; (ii) its salts; (iii) PFHxS-related compounds which, for the purposes of the Convention, are any substance that contains the chemical moiety $C_6F_{13}S$- as one of its structural elements and that degrades to PFHxS.	355-46-4, and others [36 group members listed at ECHAs website]10		X
C9-C14 linear and/or branched perfluorocarboxylic acids (C9-C14 PFCAs), their salts and C9-C14 PFCAs-related substances. Any C9-C14 PFCA-related substance having a perfluoro group with the formula C_nF_{2n} +1- directly attached to another carbon atom, where n = 8, 9, 10, 11, 12, or 13, including their salts and any combinations thereof. Any C9-C14 PFCA-related substance having a perfluoro group with the formula C_nF_{2n} +1- that it is not directly attached to another carbon atom, where n = 9, 10, 11, 12, 13 or 14 as one of the structural elements, including their salts and any combinations thereof.	Specific substances listed below and others	Entry 68	

[9] https://echa.europa.eu/List-of-substances-proposed-as-pops/-/dislist/details/0b0236e1849a8bdf

[10] https://echa.europa.eu/substance-information/-/substanceinfo/100.259.368

Substances	CAS No (as indicated in the legislation)	REACH Annex XVII	POPs Regulation
Specific examples listed:			
Perfluorononan-1-oic-acid (PFNA) (C9 PFCA)	375-95-1		
Nonadecafluorodecanoic acid (PFDA), (C10 PFCA)	335-76-2		
Henicosafluoroundecanoic acid (PFUnDA)(C11 PFCA)	2058-94-8		
Heptacosafluorotetradecanoic acid (PTFEDA)(C12 PFCA)	376-06-7		
Pentacosafluorotridecanoic acid (PFTrDA)(C13 PFCA)	72629-94-8		
Tricosafluorododecanoic acid (PFDoDA)(C14 PFCA)	307-55-1		
(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl) Silanetriol Any of its mono-, di- or tri-O-(alkyl) derivatives (TDFAs) in spray products. Specific examples listed:	Specific substances listed below and others	Entry 73	
Trimethoxy(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)silane	85857-16-5		
Triethoxy(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)silane	51851-37-7		
Undecafluorohexanoic acid (PFHxA), its salts and related substances (C6 PFCA)	307-24-4	Restriction proposal supported by RAC and SEAC	
Per- and polyfluoroalkyl substances (PFASs) in fire-fighting foams.	All PFASs for the purpose	Restriction proposal supported by RAC and SEAC *	
Per- and polyfluoroalkyl substances (PFASs) All PFAS except substances that only contains the following structural elements: CF3-X or X-CF2-X', where X = -OR or -NRR' and X' = methyl (-CH3), methylene (-CH2-), an aromatic group, a carbonyl group (-C(O)-), -OR'', -SR'' or -NR''R'''; and where R/R'/R''/R''' is a hydrogen (-H), methyl (-CH3), methylene (-CH2-), an aromatic group or a carbonyl group (-C(O)-).	Nearly all PFASs	Restriction proposal under evaluation by RAC and SEAC	

* RAC and SEAC: Committee for Risk Assessment and Committee for Socio-economic Analysis appointed by ECHA.

1.3.2 National restrictions on the use of PFASs

Since 2020, Denmark has had a national restriction on the use of food contact materials made of paper and cardboard in which PFASs have been used (BEK no. 681 of 25/05/2020). The said food contact materials may not be placed on the market unless a functional barrier is used in the product, whereby migration of the PFASs into the food is avoided. The Danish Food Authority has introduced an indicator value which corresponds to 10 µg organic fluorine per cubic decimeter (dm^3) of paper when the paper has a weight of 0.5 g/dm^3. Content below the indicator value is considered unintentional background contamination.

A national ban prohibiting the import, sale and use of PFAS-containing fire-fighting foam concentrate at fire drill sites entered into force in Denmark on January 1, 2024, with prohibition deadlines for import and sale of 1st January 2024, and use from 1st July 2024, respectively (BEK no. 1360 of 27/11/2023).

1.3.3 Danish quality criteria for drinking water, groundwater, soil and sewage sludge

Danish quality criteria for drinking water, groundwater, soil and sewage sludge are listed in Table 4. The criteria for sewage sludge and soil are indicative.

The criteria concern the sum of 22 PFASs (designated $PFAS_{22}$) with specific criteria for four of these (designated $PFAS_4$ marked underlined below). Of the 22 PFASs, 20 belong to the group of PFAA, whereas two are PFAA precursors:

- **PFCAs:** PFBA, PFPeA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFUnDA, PFDoDA, PFTrDA (i.e. C4-C13 PFCAs),
- **PFSAs:** PFBS, PFPeS, PFHxS, PFHpS, PFOS, PFNS, PFDS, PFUnS, PFDoS, PFTrS (i.e. C4-C13 PFSAs),
- Perfluoroalkane sulfonamides: PFOSA, and the
- **Fluorotelomer compound**: 6:2 FTS - the only polyfluorinated compound.

Furthermore, a drinking water quality criterion is established for TFA.

Table 4. Danish quality criteria for drinking water, groundwater, soil and sewage sludge

Substances	Drinking water at consumer water taps, µg/L *	Groundwater, µg/L **	Soil, mg/kg **	Sewage sludge, mg/kg ***
TFA (trifluoroacetic acid)	9	-	-	-
Sum of 22 PFAS	0.1	0.1	0.4	0.4
Sum of 4 PFAS: PFOA, PFOS, PFNA, and PFHxS	0.002	0.002	0.01	0.01
Pesticides (incl. PFAS pesticides)	0.5 (total pesticides and degradation products) 0.1 (individual pesticides)	0.5 (total pesticides) 0.1 (individual pesticides)	-	-
Non-relevant degradation products from pesticides	0.1	-	-	-

* Statutory Order on water quality and supervision of water supply facilities (BEK nr 1023 of 29/06/2023). [Bekendtgørelse om vandkvalitet og tilsyn med vandforsyningsanlæg].

** Danish EPA, 2021. List of quality criteria in relation to contaminated soil [Liste over kvalitetskriterier i relation til forurenet jord]

*** Danish EPA, 15 October 2021: Indicative limit value according to letter. It is expected that an updated binding limit value will be implemented in 2023. A study on derivation of cut-off values for PFASs in sewage sludge commissioned by the Danish EPA has suggested a new value for 4 PFASs at 0.015 mg/kg (Jensen et al., 2023). The study further concludes that a limit value for 22 PFASs in sewage sludge with a large margin of safety could be set at between 0.05 and 0.1 mg/kg but notes that the scientific basis for the estimate is quite uncertain.

1.3.4 Danish quality criteria for the water environment

Danish quality criteria for the water environment are listed in Table 5 (Danish EPA, 2023f).

The environmental quality criteria below are set for the sum of “PFOA equivalents” of 24 PFASs with the exception of the sediment quality criterion, which is only is determined for PFOS. The PFOA equivalents for each substance are calculated by multiplying measured concentrations by a Relative Potency Factor (RPF) established at EU level by the Joint Research Centre (JRC, 2022).

Compared to $PFAS_{22}$, the 24 PFASs includes seven new substances and excludes five.

Table 5. Danish quality criteria for the water environment (Danish EPA, 2023f)

Type of criteria	Designation	Value *
Water quality criterion, freshwater	$VKK_{freshwater}$	0.0044 µg/L **
Water quality criterion, marine water	$VKK_{marine\ water}$	0.0044 µg/L **
Short-term water quality criterion, freshwater	$KVKK_{freshwater}$	Not determined
Short-term water quality criterion, marine water	$KVKK_{marine\ water}$	Not determined
Sediment quality criterion, freshwater	$SKK_{freshwater}$	13.5 µg/kg dry weight (5% OC) (PFOS) 270 µg/kg dry weight x f_{OC} (PFOS) ***
Sediment quality criterion, marine water	$SKK_{marine\ water}$	Not determined
Biota quality criterion, secondary poisoning, freshwater	$BKKsec.poison._{freshwater}$	22.3 µg/kg wet weight (fish) 6.2 µg/kg wet weight (mussel)
Biota quality criterion, secondary poisoning, marine water	$BKKsec.poison._{marine\ water}$	6.99 µg/kg wet weight (fisk) 2 µg/kg wet weight (mussel)
Biota quality criterion, human consumption	HKK	0.077 µg/kg wet weight

* The environmental quality criteria are set for the sum of “PFOA equivalents” with the exception of the sediment quality criterion. By "PFOA equivalents" it must be understood that RPF (Relative Potency Factors) is used to calculate a sum criterion for the 24 PFASs specified in table 1 in JRC (2022 as cited by Danish EPA, 2023f). ** The values are set on the basis of human consumption of drinking water (JRC, 2022 as cited by Danish EPA, 2023f).***f_{OC}: fraction of organic carbon. OC: organic carbon.

1.4 Methodology

1.4.1 Substance flow methodology

The substance flow analysis is undertaken in accordance with the principles of the Danish Environmental Protection Agency’s paradigm for substance flow analyses (Lassen and Hansen, 2000).

Overall scope of the analysis. The reference year of the analysis is 2021, but in case data for this year were not available, data from the closest year(s) are used for approximation. The analysis concerns the flow of the substances through Danish society (the Technosphere) and the releases to the environment in the reference year. The further fate of the substances in the environment - e.g. PFASs released to soil in 2021 later leading to contamination of surface waters or groundwater - is outside the scope of the study. The Danish Regions have estimated that the number of potentially PFAS-contaminated sites is 15,000[11]. In Denmark, more than 4,000 locations are known where waste has been landfilled; the locations make up a total area of around 143 km² (Clausen and Kalvig, 2020). Releases from contaminated sites such as fire-fighting training fields or old non-managed landfills are included only to the extent that the leachate is discharged to sewage treatment plants, i.e., leading back to the Technosphere. Likewise, the future fate of the substances disposed of to landfills is outside the study scope. One exception from this principle is that the atmospheric deposition of PFASs over land and surface water (defined as the Danish sea area) is included in the substance balance in order to be able to compare inputs from atmospheric deposition with inputs to land and surface water from land-based sources. Direct discharges to Danish waters from ship traffic are not included in the substance balance.

[11] https://www.jordforureninger.dk/fokusomrader/pfas/

Potential for the formation of persistent degradation products. The analysis sums up and compares the total quantities of PFASs independently of their potential for formation of persistent degradation products. One tonne of a specific PFAS active substance in a plant protection product may, by way of example, have another potential for the formation of the persistent degradation product TFA than one tonne of another active substance or some specific fluorinated gas. The results must therefore be interpreted with caution as regards the potential for the formation of persistent degradation products and the risk associated with these. This possibility is particularly prominent when atmospheric deposition of degradation products is compared with releases of the parent precursor substances.

Use of data from the PFAS restriction proposal. Limited information is available on quantities of PFASs used in various articles and preparations in Denmark. Therefore, the estimated quantities for most of the application areas are based on extrapolation of consumption estimates for PFASs at EU27 or EEA[12] level from the PFAS restriction proposal. The restriction proposal adds quantities used for production and quantities used in the use phase, as the objective is to estimate total releases from all life cycle phases. A possible consequence of this approach is that there might be some double counting as regards the total quantities used. For those application areas where it is explicitly indicated which of the quantities concern production processes, these were subtracted for the extrapolation if it was clear that the production processes do not take place in Denmark. For the consumption of fluorinated gases and active substances in plant protection products and biocidal products, quantities are available from national statistics, whereas for the use in firefighting foams, estimates are based on the restriction proposal for firefighting foams (ECHA, 2022). The consumption estimates for PFAS at EEA level are indicated as low, high and midpoint estimates in the PFAS restriction proposal. The midpoint estimates are used for risk estimates in the restriction proposal. However, the midpoint estimates are not necessarily the “best estimate” or the “most likely” estimate, but it is not indicated in the PFAS restriction proposal where the most likely value is within the range between low and high estimate. Consequently, the midpoint estimate is used for estimation of midpoints estimates for Denmark.

Release estimates. The releases of the PFASs are calculated using mass balance principles from the estimated consumption (quantities placed on the market) in the reference year and emission and distribution factors. The emission factors express the fraction released to the environmental compartments from the actual activities in a given life-cycle step, whereas distribution factors express the distribution of the PFASs to the next step in the life cycle (e.g. solid waste treatment or sewage treatment). The estimated releases using the mass balance principles are, to the extent data are available, compared with measured releases from solid waste and sewage treatment. The information is combined into three substance flow balances for PFASs presented in Chapter 6.

Trends in consumption. The releases of the substances from the use phase reflect the quantities accumulated in society and, furthermore, the quantities disposed of reflect the consumption one average product lifetime ago. In order to take this into account, the analysis includes a trend factor which expresses the trends in consumption. For an article with an average lifetime of 10 years the trend factor expresses the consumption in 2011 divided by the consumption in 2021. Trend factors are applied in application areas where the available data indicates a particular trend which may significantly influence the results. For all other application areas, a factor of 1 is applied (corresponding to steady state).

Uncertainties. The paradigm prescribes the use of ranges to illustrate the uncertainty on any estimate. As many of the estimates are based on extrapolation of uncertain estimates of

[12] EEA: European Economic Area. Includes EU countries and Iceland, Liechtenstein and Norway. The estimates provided in the PFAS restriction proposal concern the EEA.

consumption of the PFASs at EU27 or EEA level, in general, limited information is available for assessing the actual uncertainties when data are extrapolated to the Danish situation. Furthermore, the uncertainties about consumption volumes are multiplied with uncertainties on emission and distribution factors, which further increases the uncertainties about releases.

For this reason, a simple indication of expected uncertainty levels, based on the authors' best estimates, is applied to summary tables:

- Low: The actual value is most likely within a range of ±25% (typically data based on actual national statistics and where emission factors are well described)
- Medium: The actual value is most likely more than 1/3 and less than three times the best estimate (typically data for applications where the use in Denmark is most likely quite similar to the EU average). In these cases, the actual value is considered likely to be within the right order of magnitude
- High: The actual value may be less than 1/3 or more than 3 times the best estimate (applied for very uncertain use estimates and emissions where the emission factor is roughly estimated). In these cases, the actual value may be outside one order of magnitude.

The uncertainties are reflected in the summaries and conclusions of the substance flow analysis.

1.4.2 Derivation of emission factors and distribution factors

Emission factors for releases to air, soil, waste water and surface water from the use phase are based on the PFAS restriction proposal in most cases. It is stated in the proposal that emission factors are largely based on the default emission factors (ERC) from the REACH guidance document on environmental risk assessments (ECHA, 2016). The use of industry-specific emission factors (SPERC), typically developed by European trade associations, was assessed for the PFAS restriction proposal with the conclusion that the SPERCs are generally not specific for PFAS, and the use of SPERC did not lead to a better analysis than using the ERC (ECHA, 2023). The ERCs are worst-case emission factors and may likely overestimate the actual releases. The ERCs are used in the PFAS restriction proposal in the absence of release factors based on actual studies. More specific emission factors have similarly not been available for this study; the ERCs used in the PFAS restriction proposal are consequently used in this study as well. In tables where releases based on ERCs are combined with releases derived from actual measurement, it is indicated which of the calculated releases are based on ERCs.

For fractions that are not discharged directly to the environment, distribution factors are determined, primarily based on Danish data and data on the disposal pattern for polymeric PFASs in the EU (Conversio, 2020).

1.4.3 Conversion from target PFASs to total PFASs

To determine PFASs in the various flows, it is common to measure the sum of a number of indicator PFASs, e.g. the sum of 22 PFASs used for monitoring PFASs in soil and groundwater in Denmark. A number of studies have demonstrated that the target (specifically measured) PFASs only account for a part of the total PFASs in the flows. In order to convert measurements of target PFASs to total PFAS concentrations, available studies of concentrations of conventional target PFAS, additional target PFASs and total extractable organic fluorine (EOF) are reviewed, and a convention factor estimated where possible. However, data for such conversions are often scarce and varying. The use of such conversions may tend to underestimate the total PFAS tonnages due to the large number of, and variety among, the substances in the PFAS substance group.

1.4.4 Data from stakeholders

Data from key industry and trade associations as well as waste and sewage treatment associations were collected through e-mail and phone contacts to the following associations: Dansk Industri, Dansk Erhverv, Plastindustrien i Danmark, Danmarks Farve- og Limindustri, Affalds- og ressourceindustrien, Procesindustrien, Medicoindustrien Medtech, Dansk Mode & Textil, Dakofa, Brancheforeningen Cirkulær, and Danva.

Furthermore, selected industrial users of PFASs were contacted in order to assess to what extent processes described in the PFAS restriction proposal take place in Denmark. Within the framework of the study, it has only been possible to directly contact a few companies.

1.4.5 Use of statistics

Danish Product Registry. A search of substances notified to the Danish Product Registry was undertaken on the basis of a gross list of PFASs from the US EPA with approximately 10,000 PFASs. For each of the substances, quantitative data on import/production and export and concentration in product was extracted, along with information on number of preparations and notifiers. The results were grouped into the three major substance groups used for this study, based on information in the OECD (2018) list and the US EPA gross list. For the polymers, the grouping into side-chain fluorinated polymers and other fluoropolymers was done on the basis of the structure category names in the OECD list, which distinguishes between fluoropolymers and various fluorotelomer-based side-chain fluorinated polymers. The results are provided in Appendix 3 and the methodology and results further described in section 2.1.1.

Statistics Denmark. An extract from Statistics Denmark of imports, exports and production covering commodity codes that specifically include PFASs is provided in Appendix 4. As a basis for the extraction, a search in the Combined Nomenclature[13] for the text string “fluor” was undertaken and all commodity codes which include fluoropolymers and other PFASs (mainly PFOS derivatives and fluorinated gases) were selected. Data on commodity codes covered by the Danish F-gas inventory (Poulsen, 2023) were not extracted, as the study draws on the annual inventories for these substances as described further below.

Active substances in pesticides. Quantities of PFAS active substances in pesticides sold in Denmark in 2019-2021 were extracted from the Danish pesticides statistics (in Danish, “Bekæmpelsesmiddelstatistikken”, Danish EPA, 2023b). The search for PFAS active substances was based on the non-exhaustive lists of PFAS active substances in plant protection products and biocidal products in the PFAS restriction proposal (ECHA, 2023) supplemented by 5 PFAS active substances identified by the Danish Environmental Protection Agency. The data are described in section 2.2.16. For biocidal products, it was furthermore assessed as to whether PFAS active substances of biocidal products were registered in the Danish Product Registry, which was not the case.

F-gas statistics. For the majority of the fluorinated gases, detailed annual surveys of the consumption and emission of F-gases in Denmark distributed across main application areas are available. The F-gases are fluorinated greenhouse gases addressed by the EU F-Gas Regulation (Regulation (EU) No 517/2014). The study draws on the most recent of the surveys, which cover 2021 (Poulsen, 2023). For the calculation of emissions from the current uses of the gases, the survey takes historical consumption into account. The specific F-gases that are not PFASs (e.g. SF6) are subtracted from the total, and information on some PFASs that are not included in the F-gases inventory is added as described in section 2.2.15.

Waste statistics. Total quantities of waste disposed of for incineration and landfill were derived from the Danish Waste Statistics (Danish EPA, 2022). The most recent statistics (when

[13] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=OJ:L_202302364

the relevant sections were drafted) concern 2020. The use of the statistics is further described in section 2.1.2.

1.4.6 Designation of groups of PFASs

The report uses two types of designations for total concentration of a number of analysed PFAS:

- $PFAS_4$ and $PFAS_{22}$ for the total concentration of the groups of PFASs used for monitoring of PFASs in various media in Denmark, as described in section 1.3.3.
- ∑14 PFAS; ∑16 PFAS, ∑99 PFAS for groups of PFASs not defined as part of a monitoring regime in Denmark. The actual PFASs may vary; as an example, two studies of ∑16 PFAS may not necessarily include exactly the same PFASs.

2. Uses in Denmark

2.1 Use in production processes in Denmark

2.1.1 Data from the Danish Product Registry

A dataset was received for this study from the Danish Product Registry administered by the Danish Working Environment Authority (WEA, 2023). The dataset is based on information on PFASs as notified by importers and producers to be used in professional products and mixtures. Information reported by fewer than 3 companies or for fewer than 4 specific products was not quantified for the individual substances in the dataset due to confidentiality, but this information was included in totals. The data extract was done in 2023 but reports annual tonnages relevant for recent years.

Only PFASs that are themselves classified as hazardous, or that form part of products or mixtures with other hazardous chemicals, are required to be registered in the Product Registry. Some PFASs are currently not classified as hazardous with a harmonised classification; therefore, the Register does not necessarily include all PFAS amounts placed on the market in Denmark.

Of the 70 substances reported, 17 substances were named with individual quantitative data, and the remaining 53 substances were listed, but their tonnages were reported as sums for confidentiality reasons, not individually. The 70 substances were imported to Denmark by 109 companies in 808 products in total.

For substances with sufficient numbers of products notified and companies notifying, the distribution across applications was given in the dataset received from the Danish Product Registry (WEA, 2023). These data are summarised in Table 6 by main PFAS group. As can be seen, the major application areas were refrigerants (PFAS gases), paints and varnishes, and printing inks. Note that all substance tonnages presented in this report section were calculated by the Working Environment Authority using maximum reported substance concentrations (within a given range), meaning that they are expected to overestimate the PFAS tonnages of the notified substances for the actual reported products.

Table 6. Distribution of PFAS maximum consumption* of notified substances in Danish production by application as per 2023 (Source: The Danish Product Registry; WEA, 2023)

Identified applications	PFAAs and precursors, t/y	PFAS gases, t/y	Polymeric PFASs, t/y	Total PFAS, t/y (rounded)
Paints and varnishes	0.3	0	7	7
Refrigerants	0	38	0	38
Surface treatment of metals	0	0	0.3	0.3
Glues	0	0	0.1	0.1
Lubricants	0.0001	0	0.7	0.7
Printing inks	0	0	4	4
Fire extinguishers	0.1	0	0	0.1
Total identified PFASs (rounded)	**<0.4**	**<38**	**<12**	**<51**
Confidential uses				<14
Total PFAS use				**<65**

* Consumption estimated as production/import subtracted from export.

The individually quantified substances dominating the (maximum) consumption in Danish industry were, according to the Danish Product Registry (WEA, 2023):

- 1,1,1,2-Tetrafluorethan (HFC-134a; <29 t/y) - a refrigerant
- 2,3,3,3-Tetrafluorprop-1-en (HFO-1234yf; <13.3 t/y) - a refrigerant, and
- Polytetrafluoroethylene (PTFE; 13.2 t/y)) - used in paints and varnishes (<7 t/y), printing inks (<4 t/y), lubricants and glues.

Two of the 17 substances quantified individually were gases, 7 were polymers and 8 were within the group of PFAAs and precursors.

For other individually quantified substances, see Table 110 in Appendix 3. These all have maximum consumptions of below 0.4 t/y, but note that in principle, some substances not quantified individually in the table may have higher consumption than 0.4 t/y (if used in <4 products or produced/imported by <3 companies).

Table 110 in Appendix 3 shows maximum import (/production[14]), maximum export and the calculated maximum-based net consumption in Danish production for the 17 individually quantified substances, and totals that also include the sums for substances with no disclosed individual tonnages. Applications are shown for substances with sufficient product types and companies involved. The total maximum-based consumption for the 17 substances quantified individually was <57 t/y, whereas the total maximum-based consumption for the remaining 53 substances was <8 t/y, indicating that the individually quantified substances may indeed be considered among the more common PFASs applied in Danish production.

The largest sectors in terms of PFASs consumption were, according to the Danish Working Environment Authority (WEA, 2023):

- “Manufacture of other machines for general purposes” (<19 t/y)
- “Maintenance and repair of motor vehicles” (<13 t/y; primarily refrigerants)

[14] To the authors’ knowledge, no production of PFASs takes place in Denmark, but the Product Registry data indicate that production of some products and mixtures with PFAS takes place.

- "Manufacture of other finalised metal products" (<6 t/y) and
- "Production of paints, varnishes, coatings, inks and sealants" (<4 t/y)

Sectors	Production and import t/y	Export t/y	Listed PFASs (prod and import, t/y)
Manufacture of other machines for general purposes	38.2	19.2	n.d.
Maintenance and repair of motor vehicles	14.5	2.0	HFC-134a (10.2)
Manufacture of other finalised metal products	5.6	5.6	TFTE (5.6)
Manufacture of machines for general purposes	4.5	3.2	TFTE (0.04)
Production of paints, varnishes, coatings, inks and sealants	4.2	4.2	n.d.
Manufacture of furniture	3.6	1.0	TFTE (2.2)

A complete list of sectors in which the registered substances were used, and the tonnages used by sector are given in Table 111 in Appendix 3; substance names are given for substances with sufficient numbers of products and companies involved.

2.1.2 Statistics on production, import and export

Data on import, export and production from Statistics Denmark are shown in Appendix 4.

Import, export and production of TFA related PFASs

The statistics from Statistics Denmark include detailed information on import, export and production of some fluorinated gases. For the majority of substances, data from the statistics are used for the annual Danish survey of the use of F-gases (Poulsen, 2023) which form the background for section 2.2.15 on applications of fluorinated gases. However, some fluorinated gases (e.g. the HFOs) are not included in the Danish F-gas survey; data for these substances have specifically been retrieved for the current study (see section 2.2.15 for details).

Import and production of polymeric PFASs in primary form

Fluoropolymers. The average annual net import of PTFE in primary form (i.e. pure PTFE not mixed with other substances) during the period 2020-2022 was 890 t/y. In addition, a registered average annual production in Denmark of 27 t/y is registered for the period. There is no primary production of fluoropolymers in Denmark; the explanation for the registered production is likely that a fraction of the imported PTFE is repacked before it is sold on the Danish market. In Denmark, the PTFE is used for coating of a large number of different items to a large extent. A significant fraction of the PTFE is used by specialised companies which produce coated parts for various industries such as medical, oil & gas, machine, cleantech, food, heavy chemical, and paint and varnish. The total quantity of PTFE converted into final products in the EEA in 2020 is reported to be 22,400 t/y, which accounts for 56% of the total quantity of fluoropolymers converted into products (Conversio, 2020). With an import of 890 t/y in primary form, Danish industry uses approximately three times more PTFE than the EEA *per capita* average. In section 2.2, the use of polymers is allocated to the various application areas and the possible releases from the production is allocated to these application areas. However, in practice, the conversion of the fluoropolymers takes place within a limited number of companies within the plastics industry.

For other fluoropolymers, no import, export or production of the polymers in primary form is recorded. At EEA level, other fluoropolymers account for 36% of the total (of which fluoroelastomers account for 8%), corresponding to 14,400 t/y (Conversio, 2020).

Fluoroelastomers. The average annual net import of fluoroelastomers in pure form during the period 2020-2022 was 25 t/y. Fluoroelastomers have a number of applications as rubbers and processing aids. The only application in Denmark identified is as a processing aid in the manufacture of thin plastic film packaging, specifically for "stretch hoods" used for pallet packaging. According to the Danish Plastics Federation, about 5 companies in Denmark are involved in the production of the relevant types of films. One of the companies specifically indicates on their website that the company, "like other film producers", uses fluoropolymers as a polymer processing aid. While the net import observed is in accordance with the *per capita* consumption for generic packaging in the EEA, industry contacts informed the study that fluoroelastomers for the purpose are imported already mixed into the raw materials (usually PE), or as masterbatch, also meaning mixed with PE but with higher elastomer concentration. Whether such masterbatch is registered as fluoroelastomers in the trade statistics is not known, but it may indicate that there are also other uses of fluoroelastomers in production in Denmark.

According to Conversio (2020), the FKM fluoroelastomers in the EEA accounted for 8% of the total amount of fluoropolymers converted into products in the EEA, corresponding to 3,200 t/y. The FKM fluoroelastomers are rubbers used for high-performance tubes, gaskets, O-rings, etc. No production of articles of fluoroelastomer rubbers in Denmark has been identified, but it cannot be excluded that some production takes place.

Summary. In summary, the overall consumption of fluoropolymers in primary form in Danish industry may be about twice the EEA average. Possible release from production is included in the application-specific chapters in section 2.2, in the absence of detailed dates for its use in Denmark. The distribution between application areas is likely significantly different from the EEA average, but the uncertainty introduced by the allocation across application areas is considered small compared to the uncertainty about the actual releases.

Import of polymeric PFASs in semi-manufactures

No data on import of polymeric PFASs in semi-manufactures for production processes in Denmark has been obtained, as none of the commodity codes of the Combined Nomenclature specifically concern PFAS-containing semi-manufacturers.

Import and production of PFAAs and precursors

As discussed in Appendix 4, import of a number of PFAS-related substances is registered in the trade statistics from Statistics Denmark. As discussed in the Appendix, the registered import of the specific substances is most likely an error and the importers may have used the specific commodity codes in the absence of commodity codes for other non-polymeric PFAS. The data from the Product Registry does not confirm any use of the specific substances listed in the trade statistics.

2.1.3 Other information on PFASs in production processes

In the past, PFASs were used for production of carpets in Denmark and may have accounted for one of the major applications for production processes at the time (Jensen et al., 2008). According to the 2022/2023 sustainability report from the only large Danish manufacturer of carpets, the company has not used any kind of PFASs the last 5 years. [15]

According to the trade organisation Danish Fashion and Textile [Dansk Mode & Textil] there is no production of PFAS treated fabric, textiles or apparel in Denmark. It can, however, not be totally excluded that some companies, e.g. companies that are not member of the trade association, produce PFAS containing products.

[15] https://catalogs.egecarpet.com/8054033/?page=50

2.2 Use in articles and mixtures

2.2.1 Textiles, upholstery, leather, apparel and carpets

Applications

Sub-category uses relevant for textiles, upholstery, leather, apparel and carpets applications (abbreviated as TULAC applications) listed in the PFAS restriction proposal are shown in Table 7.

Table 7. Major use categories, examples of sub-category uses and technical function of PFASs for TULAC applications (ECHA, 2023)

Major use category	Examples of sub-category-uses	Technical function of PFASs claimed by stakeholders	Assumed PFAS main groups
Home textiles	Carpets and rugs	Water repellence, oil repellence	PFAAs and precursors (side-chain fluorinated polymers)
	Curtains and blinds	Water repellence, oil repellence	PFAAs and precursors (side-chain fluorinated polymers)
	Textile based coverings (e.g. fabrics for soft-furnishings, tablecloths, bedding)	Water repellence, oil repellence	PFAAs and precursors (side-chain fluorinated polymers)
Consumer apparel	Indoor and outdoor wear	Water repellence	Fluoropolymers (PTFE) PFAAs and precursors (side-chain fluorinated polymers)
	Sportswear	Water repellence, oil repellence	PFAAs and precursors (side-chain fluorinated polymers)
	Footwear	Water repellence, oil repellence	Fluoropolymers (PTFE) and PFAAs and precursors (side-chain fluorinated polymers)
	Accessories (e.g. umbrellas, bags, wallets)	Water repellence	Fluoropolymers (PTFE) and PFAAs and precursors (side-chain fluorinated polymers)
Professional apparel	Professional sportswear and footwear	Water repellence, oil repellence	
	PPE for industrial and professional use (other than sportswear)	Water repellence, oil repellence, stain-resistance, soil protection	Fluoropolymers (PTFE) and PFAAs and precursors (side-chain fluorinated polymers)
Technical textiles	Outdoor technical textiles (e.g. canvas, awnings, tarps, tents, sails, rope)	Water repellence, oil repellence, stain-resistance, soil protection	Fluoropolymers (PTFE) and PFAAs and precursors (side-chain fluorinated polymers)
	Medical applications (e.g. surgical drapes, gowns, curtains)	Water repellence, oil repellence, stain-resistance	Fluoropolymers (PTFE) and PFAAs and precursors (side-chain fluorinated polymers)
	High performance membranes (e.g. automotive and medical)	Water repellence, oil repellence, stain-resistance, thermal stability	Fluoropolymers (PTFE etc.)
Leather applications	Leather based goods (e.g. leather bags, wallets, belts)	Water repellence, oil repellence	PFAAs and precursors (side-chain fluorinated polymers)
	Indoor and outdoor wear	Water repellence, oil repellence	Fluoropolymers (PTFE) and PFAAs and precursors (side-chain fluorinated polymers)
	Footwear	Water repellence, oil repellence	Fluoropolymers (PTFE) and PFAAs and precursors (side-chain fluorinated polymers)
	Professional sportswear and footwear	Water repellence, oil repellence	Fluoropolymers (PTFE) and PFAAs and precursors (side-chain fluorinated polymers)
Other	E.g. home fabric treatments (sprays) for leather/textiles	Water repellence, oil repellence, stain-resistance, soil protection	PFAAs and precursors (side-chain fluorinated polymers)

Types of PFASs used

According to the PFAS restriction proposal, the majority of amounts reported used by stakeholders in the TULAC sector in the EEA are fluoropolymers (particularly PTFE, e.g., in "Goretex" membranes to make the apparel waterproof and breathable) and side-chain fluorinated polymers which provide dirt and water repellency.

Notably, all the PFASs reported to be used in professional textiles were PTFE or fluoropolymers of >20 carbon chain length.

The side-chain fluorinated polymers have a wide range of applications in TULAC, as shown in the table below.

Table 8. Side-chain fluorinated polymers used for TULAC applications (ECHA, 2023)

Sub-category hydrophilic group	Applications
Alcohols, silanes, alkoxylates, fatty acid esters, adipates, urethanes, polyesters, acrylates	Soil/water repellence for carpet, fabric/upholstery, apparel, leather, metal/glass
Phosphate esters	Soil/water repellence for carpet, fabric/upholstery, apparel, leather, metal/glass. Oil/water repellence for plates, food containers, bags, wraps, folding cartons, containers, carbonless forms, masking papers

Production in Denmark

According to the trade organisation Danish Fashion and Textile [Dansk Mode & Textil], no production of PFAS treated fabric, textiles or apparel occurs in Denmark. Accordingly, there are no explicit registrations of PFAS use in the Danish Product Registry of textile production (WGA, 2023). The final apparel is typically imported from countries outside the EU. The major producers of carpets in Denmark, which are organised in Danish Fashion and Textile, does not use PFASs today but it may still be the case that small producers of carpets, not members of the organisation, still use PFASs in the production of carpets. However, there are no explicit registrations of PFAS use in the Danish Product Registry of Danish textile or carpet production using PFASs (WEA, 2023).

Quantities used

The quantities of PFASs used by main groups in the EEA in 2020 are shown in Table 9**.** A more detailed breakdown by PFAS sub-groups is shown in Table 10. Similar detailed breakdowns are not provided in the PFAS restriction proposal for most other application areas.

According to the information received in the data collection for the PFAS restriction proposal, around 80% of the estimated total tonnage is fluoropolymers. The use of polymeric PFASs in the subgroup "other" covers two general groups: unique polymer substances for various purposes (applications not specified), and a range of reaction products, which are either oligomeric or polymeric (applications not specified).

The results indicate that the key TULAC sectors using PFASs are consumer apparel, followed by home textiles and technical textiles, but with a significant quantity in the "other" category. This information on the use of PFASs per sub-category of TULAC is associated with some uncertainty because tonnages reported for some sub-categories in the PFAS restriction proposal were split equally across the subcategories when there was no detailed information. ECHA (2023) notes that no information was available from consultations on leather uses of PFASs.

The PFAS restriction proposal estimates that between 41,000 and 143,000 t/year of PFASs are used for TULAC applications in the EEA annually. The proposal notes that the

consumption estimates for the TULAC applications might include some degree of double counting of “functional PFASs”, precursors and intermediates. The reason for this is that it has been difficult to distinguish between these groups in the data collection; there is therefore a risk that precursors were calculated separately and added along with the "functional PFASs" formed by these precursors, resulting in a doubled (or higher) quantity estimate. The proposal further notes that “*The report by Wood (2020) concludes that TULAC is approximately 45 000 - 80 000 t/y. Based on this, the “low estimate” (41 000 t) appears more credible than the “high estimate”.* Wood (2020b) estimates the total PFAS content of consumer apparel at 16,513 - 24,770 t/y with a midpoint at 20,641 t/y, lower than the midpoint of the PFAS restriction proposal of 27,655 t/y. Wood (2020b) does not distinguish between the types of PFAS. The estimate is based on the assumption that 20% of all indoor and outdoor wear sold contain PFASs at a concentration of 2-3%.

Additionally, it is noted that non-polymeric PFASs are used in the production of side-chain fluorinated polymers and are not in themselves present in the TULAC final product at the time of its sale to end-users, other than as impurities.

Table 9. Quantities of PFASs used by application sub-category and key substance groups in the EEA in 2020 (ECHA, 2023)

	Sums, by PFAS groups (low - high estimate)			
Sub use	Polymeric PFASs, t/y	TFA related PFASs, t/y	PFAAs and precursors, t/y 1)	Total PFASs, t/y
Consumer apparel	6,062 - 32,910	0	2,099 - 14,237	8,161 - 47,148
Professional apparel	5,119 - 18,943	0	101 - 1,101	5,220 - 20,044
Home textiles	4,920 - 22,607	0	1,310 - 4,761	6,230 - 27,368
Technical textiles	5,107 - 22,217	0	1, 095 - 4,324	6,201 - 26,541
Medical textiles	331 -1,096	0	0	7,331 -1,096
Leather applications	n.d.	0	122- 253 *	122- 253
Other	11,552 - 11,772	0	3,489 - 8,724	122- 253
Total (TULAC)	33,091 - 109,544	0	8,214 - 33,401	41,305 - 142,945

n.d.: No data. * The PFAS restriction proposal indicates “no data”. Applied from Wood (2000).

Table 10. Quantities of PFASs used by application sub-category and substance sub-groups in the EEA in 2020 (ECHA, 2023).

	Sum by substance sub-groups (low - high estimate)				
Sub use	C2- C3 PFASs, t/y	PFAA ≥C4, t/y	Side-chain fluorinated polymers, t/y	Fluoropolymers, t/y	PFPE, t/y
Consumer apparel	717 - 3,433	363 - 770	1,019 - 10,034	5,801 - 32,253	261 - 557
Professional apparel	0	1 - 101	100 - 1,000	5,119 - 18,943	0
Home textiles	717 - 3,433	363 - 770	230 - 559	4,658 - 22,049	262 - 558
Technical textiles	717 - 3,433	364 - 869	14 - 22	4,845 - 21,659	262 - 558
Medical textiles	0	0	0	331 - 1,096	0
Leather applications	n.d.	n.d.	n.d.	n.d.	n.d.
Other	0	2,422 - 6,103	1,067 - 2,621	11,551 - 11,762	1 - 10
Total (TULAC)	2,150 - 10,300	3,512 - 8,612	2,430 - 14,234	32,305 - 107,861	786 - 1,683

As mentioned above, the PFAS restriction proposal indicates that a report prepared by Wood (2020b) for the European Commission arrived at lower totals than estimated in the PFAS restriction proposal. As the majority of the estimated consumption and releases from the TULAC category concerns the sub-category "apparel", some efforts have been made to assess the consumption and release factors.

The estimated consumption of PFASs by apparel sub-category estimated by Wood (2020b) is shown in Table 11. Similar distribution by sub-category is not presented in the PFAS restriction proposal. The main category is "Indoor and outdoor wear", accounting for 83% of the total.

Table 11. Estimated consumption of PFASs by apparel sub-category (Wood, 2020)

Category	Sub-category	PFAS consumption, t/year	% of total based on averages
Consumer apparel	Indoor and outdoor wear	16,514 - 24,770	83%
	Sportswear	739 - 1,478	4%
	Footwear	538 - 806	3%
Professional apparel	Professional sportswear	47 - 93	0.3%
	Personal Protection Equipment for industrial applications	2,010 - 3,016	10%
Total		19,848 - 30,163	

Wood (2020b) bases the estimate on the use of PFASs in indoor and outdoor wear on statistics on the total consumption of indoor and outdoor wear in the EEA and assumes that 20% of the wear contains PFAS. The 20% is based on expert estimates, but the present study assesses this to be overestimated, as PFASs are used in outdoor wear only and indoor wear accounts for the majority of the wear. Using a *per capita* approach, the estimated consumption of indoor and outdoor wear containing PFASs in Denmark should be about 12,233 t/y. An alternative approach could be to use the consumption of outdoor wear as a starting point. For overcoats, car-coats, capes, cloaks, anoraks (including ski-jackets), wind-cheaters, wind-jackets and similar articles not knitted or crocheted [16], the supply in 2021 in Denmark was 4,695 t/year[17]. Outdoor trousers and coveralls for children are included in aggregate commodity codes, whereas ski equipment is included under the sub-category "sportswear". Coveralls and similar are included under professional apparel. Only some of the outdoor wear will contain PFASs. Schellenberger et al. (2019) assumes that 50% of the outdoor jackets sold in Germany in 2019 contained PFAS. In a market survey of PFASs in children's wear, Lassen et al. (2015) estimated that 10-30% coveralls for children contained PFASs. If it is assumed that jackets, and similar clothing included in the commodity codes mentioned, account for half of the outdoor wear that might contain PFAS, and that 50% of the outdoor wear contains PFASs (most likely overestimated), the total quantity would be about 5,000 t/y. This result indicates that the quantities are more likely in the lower end of the range of the estimate, based on Wood et al. (2020b) and the PFAS restriction proposal, but in the absence of more certain data, the general approach of using the midpoint of the ranges indicated by the PFAS restriction proposal is applied.

[16] Commodity codes 6201 and 6203 of the Combined Nomenclature. https://eur-lex.europa.eu/eli/reg_impl/2022/1998/oj

[17] Estimated as import + production – export extracted from "statistikbanken" of Statistics Denmark.

Assuming that the Danish input of PFASs in the TULAC sub-categories *per capita* is similar to that of the EEA, input estimates for Denmark, based on population in the EEA (2020) and Denmark (2021), respectively, have been derived in this study.

During the project period, no information was identified indicating that production of TULAC products with the use of non-polymer PFASs takes place in Denmark. As per the information mentioned above from the PFAS restriction proposal, it is assumed that besides fluoropolymers and side-chain fluorinated polymers, no other PFASs are present in the final apparel and textile products (unreacted monomers may be present in negligible concentrations). Such non-polymer PFASs are therefore only assumed present in the sub-category PFAAs and precursors, TULAC uses that include consumer products such as water-proofing sprays for outdoor textiles and leather.

In the further discussions of the results, the TULAC category was divided into two categories: “Apparel” and “textiles, upholstery, leather, and carpets”. The quantities of the “other” category from the PFAS restriction proposal were divided into groups: “other - side-chain fluorinated polymers”, assumed to be agents for home fabric treatments (sprays) for leather/textiles (mentioned in Table 7) and “other - polymeric PFASs”, while other non-polymeric PFAS is assumed to be used in production processes only.

The “other” category is as mentioned not well defined in the PFAS restriction proposal.

Table 12. Estimated consumption of PFASs in Denmark with final products by application sub-category and key substance groups for 2021; derived from EEA data for 2020 (population-based interpolation)

	Consumption with final products, t/y			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Apparel:				
Consumer apparel	250	0	70	320
Professional apparel	150	0	10	160
“Other” (side-chain fluorinated polymers)	0	0	20	20
Total apparel	*400*	*0*	*100*	*500*
Textiles, upholstery, leather, and carpets				
Total apparel				
Home textiles	400	0	100	500
Technical textiles	180	0	40	220
Medical textiles	180	0	30	210
Leather applications	10	0	0	10
“Other” (polymeric PFASs)	150	0	0	150
Total textiles, upholstery, leather, and carpets	520	0	72	592
Total (TULAC)	920	0	172	1,092

n.d.: No data.

Trends in consumption and accumulation in society

The PFAS restriction proposal presents information and assumptions for trends in consumption for the TULAC sub-categories and substance sub-groups up to 2020. These “backwards” trends influence the accumulation of PFASs in Danish society, because the input one average

product lifetime ago constitutes the output today. These growth rates - in combination with product lifetimes - were used here to estimate the total current outputs of PFASs currently being disposed of to waste. For simplicity, the same output data are used for emissions estimation (considering the associated uncertainty). In some cases, data were aggregated in this study across sub-periods, substance groups and sub-applications.

Releases and distribution factors

The PFAS restriction proposal uses ECHA (2016) standard environmental releases categories (ERCs). However, it does not fully disclose the actual allocations used between consumption of sub-categories (PFAS inputs) and specific ERCs (PFAS outputs). Furthermore, the emissions are only presented as sums for all PFASs and for all output pathways in the PFAS restriction proposal. The used ERCs applied and the corresponding emission factors are presented, but it is not indicated which ERCs are used for the different sub-categories and life-cycle steps.

Wood et al. (2020b) include a more detailed estimate by category of apparel; the consumption is, however, not distributed in polymeric PFASs and PFAAs and precursors. According to this survey, the consumer apparel represented 90% of the total PFASs in apparel and of this, the main category being “consumer apparel for indoor and outdoor use”, which represented 83% of the total. Wood et al. (2020b) do not present any documentation for use of PFASs in indoor consumer apparel; in this study, it is assumed that consumer apparel with PFASs is mainly used outdoors. The same is assumed for professional applications, although some fraction may be used indoors for protection against heat and dirt.

Based on the information given, however, the closest possible allocation to ERCs used in the restriction proposal was used for estimation of emissions from TULAC in Denmark (see ERCs and specific emission factors used in Table 13). The following exceptions apply, however:

For Denmark, in this study, emissions to water from outdoor uses are considered to have a 90/10 split to surface water and wastewater, as much of the outdoor TULAC use is deemed to take place in urban areas and releases outside urban areas would mainly be to soil.

In this study, a split between fluoropolymers, and PFAAs and precursors (incl. side-chain-fluorinated polymers) was introduced for apparels, technical textiles and medical textiles.

While the allocation of TULAC PFASs to emission scenarios (ERCs) in the restriction proposal is not fully disclosed, for indoor and outdoors scenarios applied it is stated that the ERCs selected are the same as those used in the TULAC-specific category by Wood (2020b) for the European Commission. Wood (2020b), however, only included non-fluoropolymers in their emissions estimation. As fluoropolymers in TULAC are expected to demonstrate very low emissions during use and washing, and as they are often encapsulated between other textile layers in apparels, reducing emissions of microplastic particles, the authors of the present study assume that fluoropolymers used in TULAC have considerably lower emissions than side-chain-fluorinated substances. Hence, a total emission of fluoropolymers to all pathways of 1% is assumed, meaning that 99% of the total output is considered as following the end-of-life product to waste treatment (note that re-use is considered an extension of the product lifetime).

For outdoor applications, the PFAS restriction proposal applies the following emission factors (ERC 12a, “Widespread use of articles with low release (outdoor)”): 0.05% to air, 3.2% to water (before SPT) and 3.2% to soil. These factors are applied in this study for the use of apparel and technical textiles. The releases to water are assumed to be distributed at 2.9% to sewage and 0.3% to surface water.

In terms of releases from consumer apparel some new studies are available, and it has been considered whether the emission factors should be adjusted on the basis of the results of these studies. Schellenberger et al. (2022) performed a study examining actual outdoor climate and washing/abrasion impacts on factory-applied side-chain fluorinated polymers (SCFPs) treated textile types (PA and polyester), dominant in outdoor apparel. The authors note that the results can be considered worst-case scenarios for consumer use of the apparel. The main objective of the study was not to determine typical releases but rather to analyse the degradation mechanisms and analyse the type of PFAAs released after weathering, abrasion and washing. After outdoor weathering, total fluorine (TF, an aggregate measure for PFAS content) levels in the fabrics tested were reduced by 4, 26, and 52% for C_6F_{13}, C_8F_{17}, and C_4F_9-based SCFPs, respectively, relative to unexposed controls. Loss of water repellence and colour fading was measured and followed the same pattern). The fabrics were exposed to ambient conditions during spring and summer for 9 months on a rooftop in Sydney, Australia, chosen because of its high average monthly irradiation; Schellenberger et al. (2022) characterize the study as likely reflecting a worst-case scenario. As part of the study, a number of specific PFASs were also measured and showed that PFAA concentrations increased during weathering, a result of degradation of the SCFPs. In this study, full day exposure on a rooftop in Sydney for 6 months is assessed to be significantly higher than the average service life exposure of an outdoor jacket in Copenhagen because there is significantly lower irradiation in Denmark (average monthly irradiation of 644 MJ/m² in Australia under test conditions against an average in Denmark of approximately 320 MJ/m²).[18] Furthermore, this kind of apparel is used mainly during the winter season where the irradiance in Denmark is even lower. Furthermore, the fabric was exposed for about 3,300 hours, corresponding to a daily use of the jacket of 3 hours each day during the winter season for 6 years. This study considers that the data does not allow for a realistic estimate under Danish conditions; therefore, the same emission factor as applied by ECHA (2023) is used.

The emission factors for outdoor apparel used by ECHA apparently do not take into account releases from washing (as the used ERC relates to releases from the outdoor applications). The study by Schellenberger et al. (2022) also analysed the effect of abrasion and washing after weathering of the fabric. After weathering, abrasion (Martindale test with 3000 rubs with 9 Pa) and subsequent washing, the TF levels were further reduced to 20, 47, and 71%, for C_6F_{13}, C_8F_{17}, and C_4F_9-based side-chain-fluorinated polymers, respectively, relative to unexposed controls. There were indications of loss of not only larger fibre fragments, but also smaller particles from abrasion and washing. The abrasion and following wash reduced the total fluorine content by approximately 19%. For comparison purposes, Schellenberger et al. (2019) found that the fluorine content after a Gyro wash (indicated as comparable to 2-15 domestic washes) was reduced by about 0.25% in a polyamide-treated fabric and about 0.05% in a polyester/cotton fabric. The abrasion with 9000 rubs after the extensive exposure at the rooftop applied in Schellenberger et al. (2022) must be considered a worst case of the abrasion of jacket under normal use. In the modelling of total releases, Schellenberger et al. (2019) assumes that the jackets are washed once a year. In the study of Schellenberger et al. (2019), the apparel had not been exposed to weathering and abrasion before the washing, which may increase the loses by the washes as demonstrated by the follow up study by Schellenberger et al. (2022). The actual releases under average normal conditions are likely in between the worst case of 19% in total-fluorine measured by Schellenberger et al. (2022) and the 0.25% (for 2-15 domestic washes) measured by Schellenberger et al. (2019).

It is in this study considered that the data do not allow for a more realistic estimate under Danish conditions, and the same emission factor as applied by ECHA (2023) is used for releases during use of the apparel. In the absence of releases by washing under realistic conditions,

[18] http://irradiance.dmi.dk/irradiance-data/dry-2001-2010/global-irradiance/

and with a view to the available data on PFASs in sewage (section 4.2.3) a release factor of 1% to sewage during the life of the apparel is assumed here.

The applied output distribution factors are shown in Table 13. The default ERCs include an emission factor to “water (before STP”) - the split between surface water and sewage depends on the specific release scenario.

Table 13. Assumed output distribution factors for TULAC (see text for background)

Sub-use	Output scenarios assigned here *	Air (%)	Soil (%)	Surface water (%)	Sewage (%)	Waste treatment (%)
Consumer apparel, fluoropolymers	Custom	0.008	0.496	0.050	0.446	99.0
Consumer apparel, PFAAs and precursors	Outdoor, low release, ERC10a + custom washing scenario	0.05	3.2	0.3	2.9	92.2
Professional apparel, fluoropolymers	Custom	0.008	0.496	0.050	0.446	99.0
Professional apparel, PFAAs and precursors	Outdoor, low release, ERC10a + custom washing scenario	0.4	3.2	0.3	3.9	92.2
Other, fluoropolymers	Custom	0.008	0.496	0.050	0.446	99.0
Other, PFAAs and precursors (incl. consumer impregnation products)	Custom	0.4	3.2	0.3	3.9	92.2
Home textiles	ERC11a: Indoor infrequent cleaning	0.05	0		0.05	
Technical textiles, fluoropolymers	Custom	0.008	0.496	0.050	0.446	99.9
Technical textiles, PFAAs and precursors	Outdoor, low release, ERC10a	0.05	3.2	0.3	2.9	99.0
Medical textiles, fluoropolymers	Custom	0.5			0.5	93.6
Medical textiles, PFAAs and precursors	Indoor, frequent cleaning, ERC11b	50			50	99.0
Leather applications	Outdoor, low release, ERC10a	0.05	3.2	0.3	2.9	0.0

* “Custom” is based on assumptions done as part of the current study, as explained in the main text. Other scenarios are based on the PFAS restriction proposal.

Using these output distribution factors, the estimated outputs directly to the environment and to wastewater and waste treatment from the Danish society are shown in Table 14 for apparel and Table 15 for textiles, upholstery, leather, and carpets applications.

Table 14. Estimated flows from the use phase in 2021 from apparel

Group of PFASs	Total outputs from use phase, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0.0	1.0	0.0	1.0	297	300
TFA related PFASs	0.0	0.0	0.0	0.0	0.0	0.0
PFAAs and precursors	0.3	2.3	0.2	2.7	84	90
Total PFASs (rounded)	0.3	3.3	0.2	3.7	381	390

Table 15. Estimated flows from the use phase in 2021 from other TULAC (textiles, upholstery, leather, and carpets applications)

Group of PFASs	Total outputs from use phase, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0.0	0.8	0.0	1.0	308	310
TFA related PFASs	0.0	0.0	0.0	0.0	0	0
PFAAs and precursors	0.0	1.0	0.1	1.0	70	70
Total PFASs (rounded)	0.0	1.8	0.1	2.0	378	380

2.2.2 Food contact materials and packaging

Application

According to the PFAS restriction proposal, PFASs in food contact material (FCM) and packaging are mainly used to confer oil and grease resistance in the following main applications:

- Packaging (including non-FCM packaging; PFASs are also reported used in inks and lacquers on paper/board and aluminium packaging)
- Consumer cookware
- Industrial food and feed production equipment

The packaging applications can be sub-divided as follows, based on the PFAS restriction proposal:

Food packaging:

- Greaseproof paper
- Baking paper
- Heat resistant packaging
- Other food packaging (e.g. milk containers, stretch and shrink films, pouches, frozen food packaging)
- Coating of (food and beverage) cans (often PTFE wax and micropowder PTFE are used)
- Disposable items used for food consumption such as paper plates, bowls and ice cream tubs

A major use for PFASs is application to paper and board substrate for fast food wrapping.

Feed packaging:

- Pet food
- Agricultural feed

Generic packaging:

- Paper and board for non-food/feed applications
- Folding packaging cartons, carbonless forms/pressure sensitive paper, masking papers, tablecloths, and wall papers
- Coated drums: fluorination of plastic (food or non-food) containers
- Coated chemical containment bottles used for non-food packaging
- Other packaging (coated plastic, glass, metal, cars) for non-food/feed applications
- Plastic films for health and hygiene

Processing and polymerisation aids application in especially PP and PE thin film manufacture: PFASs are also used as processing aids in the manufacture of plastic materials, including thermoplastic packaging, to improve the flow properties of the plastic, for example, in the production of plastic sheets.

Consumer cookware is subdivided as follows in the PFAS restriction proposal (non-stick coatings) for:

- Frying pans
- Baking trays and bake pans
- Sauce pans
- Cooking plates in electric appliances such as sandwich toasters, waffle irons
- Consumer bakeware including cake tins, bread-loaf tins, etc.
- Seals, O-rings, gaskets, tubing and pipes in consumer electrical equipment such as coffee machines (mentioned and described under industrial applications)
- Filters to capture contaminants from, for example, steam filtration in food processing

Industrial food processing and packaging
Industrial applications cover the equipment to produce food and feed, including packaging materials used at an industrial scale. PFASs are used in food processing equipment, primarily for their non-stick properties combined with non-reactivity with chemicals, thermal resilience during cooking and wear resistance providing durability. The majority of PFASs used in this market segment are fluoropolymers.

One of the main uses for PFASs in industrial applications is in food and feed processing lines where PFAS (polymers) provides a non-stick coating to conveyor belts, using PTFE or PVDF. PVDF is used in fabrication of industrial cookware equipment mainly for its mechanical properties and chemical resistance. Fluoropolymers are widely used in industrial bakeware moulds and trays because they provide long-lasting oil and fat-free mould release. Fluorothermoplastics and PTFE are also processed into valves and fittings for commercial food and feed products. PTFE impregnated glass cloth is commonly used in food contact applications as a release agent.

Other industrial uses, according to the restriction proposal, include:

- Piping and tubing for drinking water applications
- Filters to capture contaminants from, for example, steam filtration in food processing

- Seals, O-rings, gaskets, tubing and pipes, expansion joints
- Valves and fitments, conveyor belting, chutes, guiding rails, rollers, funnels and sliding plates, tanks, funnels, rollers, linings, blades of knives and scissors, springs, filter membranes and sensor covers, lubricants
- Re-coating of industrial bakeware.

Types of PFASs used

According to the PFAS restriction proposal, there are three main types of **PFASs used in packaging**:

- Short chain fluorotelomer side-chain (C6) polymeric PFASs, with high molecular weight acrylic polymers that contain fluorotelomer functionality to provide repellent performance.
- Perfluoropolyether (PFPE) based oil and grease repellent products.
- Fluoroplastics: FEP, PFA (perfluoroalkoxy ethanes), and FKM (fluorocarbon-based fluoroelastomer materials):
    - Largely unknown PFASs (by-products of fluorine gas treatment of plastic containers such as HDPE containers)
    - Fluorinated HDPE containers used for substances in various applications.

The PFAS restriction proposal lists the following key PFASs used in **consumer cookware**:

- Fluoropolymers:
    - PTFE (PTFE non-stick coatings normally consist of up to three coats and have an operating temperature of up to 260 °C)
    - ETFE (maximum continuous operating temperature 150 °C)
    - ECTFE
    - FEP (FEP non-stick coatings melt and flow during baking to provide non-porous films; maximum recommended use temperature 200 °C)
    - hexafluoropropylene
- PFA (perfluoroalkoxy ethanes) coatings also melt and flow during baking to create non-porous films; maximum continuous use temperature 260 °C)
- Perfluoroelastomers and FKMs
- (PTFE) coated elastomers

Types of PFASs used in **industrial applications** listed in the PFAS restriction proposal (key types), with PTFE, FEP, PFA and ETFE as the most often used:

- Fluoropolymers (PTFE, ETFE, ECTFE, FEP, Hexafluoropropylene variations, PVDF-based)
- PFA (perfluoroalkoxy ethanes);
- Perfluoroelastomers (liquid processing systems)
- PTFE coated elastomers, often used as sealings in pressure bearing equipment
- Others (PFMVE, PTFE copolymers)

Production in Denmark

There is a significant food and feed production industry in Denmark which may possibly produce products, for example food containers, that are coated with PFAS. However, PFAS coated paper and cardboard packaging availability on the market has been restricted in Denmark since 2020, as described below.

PFAS coating of various metal objects does take place in Denmark, and companies offering PFAS coating of food processing machinery have also been identified in the country. In addition, extrusion of polymer (PE) film with fluoroelastomers as processing aids has been identified as taking place in Denmark by a number of companies. According to an anonymous industry source, a major use is in "linear low-density polyethylene stretch hoods" that are used for packing various goods on pallets during transport, delivery and storage. The PFAS (polymer) processing aids stay in the produced PE film at a concentration of about 100 g/t material. Significant recycling of such PE occurs in Denmark.

Accordingly, there are registrations of PFAS use in the Danish Product Registry of Danish-produced machinery and others metal products using PFASs (WEA, 2023). However, machinery and products for the food sector are not singled out in WEA (2023); hence, no specific quantitative data are available on PFAS use in the sector.

Quantities used

Consumption estimates from end uses in the EEA for the food contact materials group (including non-food paper and some plastics packaging) in 2020 from the PFAS restriction proposal are summarized in Table 16.

Table 16. Quantities of PFASs used in FCM and packaging by application sub-category and key substance groups in the EEA in 2020 (ECHA, 2023)

	Consumption, t/y (low - high estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Surfactants in paper and board food packaging (coatings)	0	0	827 - 4,962	827 - 4,962
Generic plastic packaging & rubber (processing aids, but they stay in the packaging)	0	0	1,640 - 3,280	1,640 - 3,280
Consumer cook and bakeware	3,500 - 5,600	0	0	3,500 - 5,600
Industrial food production and pharmaceuticals	3,000 - 6,000	0	0	3,000 - 6,000
PFAS residues in packaging	0	0	300 - 600	450
Lacquers and inks on packaging (on paper and aluminium)	0	0	>>>500	500
Car wrapping	3,950	0	0	3,950
Beverage can coating	4,880	0	0	4,880
Total (FCM and packaging)	15,330 - 20,430	0	3,267 - 9,342	18,597 - 29,772

Input estimates for Denmark were derived in this study for other materials based on population in the EEA (2020) and Denmark (2021), respectively. The assumptions were that the Danish input of PFASs in the food contact materials sub-categories *per capita* is similar to that of the EEA, with an exception for paper and cardboard packaging materials for food contact. These estimates are shown in Table 17.

The Danish Statutory Order [19] (BEK) no. 681 of 25/05/2020 prohibits the placing on the market of food contact materials of paper and cardboard in which PFASs have been applied, unless a functional barrier prevents the migration of PFASs to the food. Statutory Order no. 681 entered into force on 1 July 2020, but allowed the use of non-compliant packaging materials purchased prior to that date until the purchased stock of such materials was exhausted. It is difficult to say how much PFAS-treated paper and cardboard packaging materials was released to the end-users, as well as to waste treatment, etc., in 2021, but as this substance flow analysis has relevance for the years after 2021, a decision was made to consider the PFAS input and output with PFAS-treated paper and cardboard as nil (0) in 2021 for this study. However, the PFAS restriction proposal also counts non-intentional PFAS residues in packaging materials (presumably from recycled materials), as well as in lacquers and inks used for print on various materials; both deemed as likely still present on the Danish market.

As concerns “Generic plastic packaging”, this could be expected to be relatively evenly distributed among EEA citizens, possibly with higher consumption in countries with high GDP/capita such as Denmark. Based on information from a major Danish producer of generic packaging plastics with the use of PFAS (polymers) as processing aids, it is possible that some of the consumption for this purpose (row 2 in Table 17) may in fact consist of polymers. Based on the very rough estimates for consumption of the types of generic plastic packaging in question (stretch hoods for pallet packaging), it is possible that the total PFAS consumption for generic plastic packaging may be somewhat overestimated for Denmark, or alternatively, that PFASs are used in other types of generic plastic packaging as well.

Table 17. Estimated consumption of PFASs used in FCM and packaging in Denmark with end uses in 2021 by application sub-category and key substance groups

	Consumption, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Surfactants in paper and board food packaging (coatings)	0	0	0	0
Generic plastic packaging & rubber (processing aids, but they stay in the packaging)	0	0	30	30
Consumer cook and bakeware	60	0	0	60
Industrial food production and pharmaceuticals	60	0	0	60
PFAS residues in packaging	0	0	10	10
Lacquers and inks on packaging (on paper and aluminium)	0	0	10	10
Car wrapping	50	0	0	50
Beverage can coating	60	0	0	60
Total (FCM and packaging)	230	0	50	280

[19] BEK nr 681 af 25/05/2020: Bekendtgørelse om fødevarekontaktmaterialer og om straffebestemmelser for overtrædelse af relaterede EU-retsakter (In Danish), accessed October 2023 at https://www.retsinformation.dk/eli/lta/2020/681#id63dc768c-1caa-4703-b098-01c250a0df74.

Trends in consumption and accumulation in society

The PFAS restriction proposal assumes annual growth rates of 6% for consumer cookware and 1.5% for industrial uses. However, in the total mix of inputs to society from the application group, these growth rates have minimal impacts on accumulation in society, because most of the applications are assumed to have short lifetimes (less than 1 year).

Emission and distribution factors

The PFAS restriction proposal mentions that standard ERC emission factors were used for indoor and outdoor use, respectively, for paper/cardboard and consumer and industrial cookware, etc. However, they do not mention which fractions are considered to be used indoors versus outdoors.

In Denmark, use and loss of packaging materials do take place outdoors, but these losses are considered to be relatively minor as the waste collection rate is high and, as mentioned, there are restrictions on PFAS-treated paper and board packaging materials. The use of standard ERC11a emission factors are therefore deemed relevant. Similarly, for all other food contact materials, the use of standard ERC11a emission factors is considered relevant for Denmark. The corresponding output factors are therefore 0.05% to air, 0.05% to sewage and 99.9% to waste treatment. The estimated emissions and flows from PFAS use in food contact materials in Denmark are shown in Table 18.

Table 18. Estimated flows in 2021 from food contact materials

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0.10	0	0	0.10	230	230
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0.03	0	0	0.03	50	50
Total PFASs (rounded)	**0.13**	0	0	**0.13**	**280**	**280**

2.2.3 Metal plating and manufacture of metal products

Application

The PFAS restriction proposal lists the following functions of PFASs in metal plating, either as processing aids or as the “plating” (coating) material itself, citing various original sources. Metal plating means the application on metal and plastic surfaces of principally chrome (for functional and decorative purposes), but also nickel, copper, tin, zinc (alkaline and zinc alloys), as well as coating with fluoropolymer particles onto steel.

Table 19. Applications of PFASs in metal plating and manufacture of metal products (little information is available on PFAS types used; source ECHA, 2023)

Sub use	Application
Metal plating	Mist suppressant
	Lowering surface tension of plating solution
	Pretreatment (etching) of plastic followed by electroplating (e.g. chrome coating)
	Nickel-plating: non-foaming surfactant - increasing the strength of the nickel electroplate by eliminating pinholes, cracks, and peeling; sliding characteristics to prevent seizure of parts
	Copper plating: preventing haze by regulating foam and improving stability while improving brightness and adhesion
	Tin plating: produce a plate of uniform thickness (EC, 2005; Kissa, 2001)
	Supporting the deposition of fluoropolymers onto steels for surface protection (EC, 2005).
Manufacture of metal products	Inhibit the formation of acid mist or spray over metal electrowinning tanks
	Treatment of coatings of metal surfaces, lowering the surface tension and thus promoting the flow of metal coatings and the prevention of cracks in the coating during drying.
	Use as corrosion inhibitor on steel. For this purpose, cationic and amphoteric fluorinated surfactants are used to impart a positive charge to fluoropolymer particles which facilitates the electroplating of the fluoropolymer.
	Coatings on metal
	Used for processing of aluminium e.g. during etching of aluminium to improve the efficient life of alkali baths or in the phosphating process of aluminium to dissolve the oxide layer of the aluminium.
	Cleaning of metal surfaces. The fluorinated surfactants disperse scum in molten-salt baths, speed runoffs of acid when metal is removed from the bath and increase the bath life.
	Solvent displacement drying (e.g. for water removal prior to plating, coating, and other sur-face treatments)
	Electrical insulation of bearing houses
	Seals, valves, bearing coating, hose products, tank liners, gaskets and packing in food pro-cessing, medical and pharmaceutical industries, chemical and oil industries, aerospace and automotive industries, industrial equipment for sensor technology;
	Fluoropolymers are used due to high chemical and temperature resistance, high durability (reduction of friction and wear), good sliding properties, pressure resistance
	Anti-stick coating and anti-stick parts in silicone moulding processes (e.g. automobile industry); coating of processing tools or moulds (function as mould release aid)

Types of PFASs used

According to the PFAS restriction proposal, little information is available on the plating with tin, copper and nickel. Some information indicate that C6 fluorinated substances are used in chrome plating. Under EU POP regulation (EU 2019/1021), PFOS is allowed only as mist suppressant for non-decorative hard chromium (VI) plating in closed loop systems. The ban of PFOS led to substitution with 6:2 fluorotelomer sulfonate (6:2 FTS also known as H4-PFOS) in chrome plating processes. German data confirm that this was the substitute in functional chrome plating, whereas in decorative chrome plating, both 6:2 FTS and fluorine-free wetting agents were used.

In the manufacture of **metal products,** mainly fluoropolymers and C6 fluorinated substances are used.

Production in Denmark

PFAS coating of various metal objects does take place in Denmark in the production of foods, extraction of oil and gas, chemicals, and medical products. Similarly, metal plating with PFASs may also take place in the country.

The Danish Product Registry reports registrations of PFAS use in the following sectors that relate to metals plating/coating and manufacture of machines (WEA, 2023):

- Surface treatment of metals, machine processing
- Manufacture of other finalised metal products
- Manufacture of machines and equipment, not specified elsewhere
- Manufacture of machines for general purposes

The total individually quantified consumption of PFASs for the four sectors mentioned first is <9 t PFAS/y, strongly dominated by PTFE. See Appendix 3 for additional information on Product Registry entries with PFAS.

A key player in the field of hard chrome plating in Denmark has confirmed that CAS No 27619-97-2 (3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctanesulphonic acid, 6:2 FTS) is the main PFAS used as mist suppressant in hard chrome plating. According to information from industry, consumption has been decreasing. The quantities registered in the Product Registry in 2021 are confidential. In a study on the use of PFASs in Denmark, a total of 0.18 t/y was registered in the Danish Product Registry for 2016 (Nicolaisen and Tsitonaki, 2016). This quantity is higher than the quantity of PFASs used for hard chrome plating indicated in Poulsen et al. (2011), at 10-28 kg of the pure substances.

Quantities used

The information on volumes of PFASs used in metal plating is scarce in the PFAS restriction proposal, but an estimate of 2-57 t/y (mid range 30 t/y) of 6:2 fluorotelomer sulfonate (6:2 FTS) is mentioned.

The PFAS restriction proposal cites Glüge et al. (2020), which states that an estimated 900 t PFASs (fluoropolymers) were used in the manufacture of metal products in Sweden, Finland, Norway and Denmark between 2000 and 2017. With the assumption that the four countries account for about 5.2% of the EEA population, the Dossier Submitters estimated that, on average, around 960 t of PFASs are used in the manufacture of metal products in the EEA per year.

Scaling the EEA PFAS inputs to the Danish population, the inputs to the Danish society were estimated for this study as shown in Table 20. These estimates are in agreement with the mentioned registrations in the Danish Product Registry (see above).

Table 20. Estimated consumption of PFASs in Denmark from metal plating and the manufacture of metal products in 2021

	Consumption, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Metal plating	0	0	0.4	0.4
Manufacture of metal products	10	0	0	10
Total	10	0	0.4	10.4

Trends in consumption and accumulation in society

The PFAS restriction proposal mentions that no trends information was available; hence, the growth rate was set at 0%.

Emission and distribution factors

The PFAS restriction proposal does not apply emission factors, but cites other data sources for varying emissions indications, including a total European emission tonnage of 0.5-11.4 t/y (mid-range 6 t/y) 6:2 FTS to the environment during chrome plating. The same level was confirmed in their own consultation process; hence, these values were used in their impact assessment. With a mid-range input of PFASs (6:2 FTS) to chrome plating of 30 t/y, the total emission to the environment equals 20% of the 6:2 FTS input. However, other sources cited claim that no PFASs are carried over to the products. Also, the restriction proposal cites (Hauser H., 2020) for the following emission distribution for the fluorosurfactants: 50-85% via wastewater, 0.1-24% via waste (e.g. metal hydroxide sludge) and <0.1% via exhaust air (Hauser H., 2020). This incomplete, and potentially contradictory, information is interpreted in this study as 0.1%*20% = 0,02% being emitted to air, 85%*20% = 17% being released to wastewater and the rest, 82.98%, being transferred to waste management.

For manufacture of metal products, the PFAS restriction proposal states that no information was available on emissions. In this study, however, the output distribution mentioned above for metal plating was applied as a proxy for manufacture of metal products.

The resulting estimates of emissions and other flows of PFASs from metal plating and manufacture of metal products in 2021 in Denmark are shown in Table 21.

Table 21. Estimated flows from metal plating and manufacture of metal products in 2021

Group of PFASs	**Total outputs, t/y**					
	Air	**Soil**	**Surface water**	**Sewage**	**Waste treatment**	**Total outputs (rounded)**
Polymeric PFASs	0	0	0	1.7	10	10
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0	0	0	0.07	0.33	0.4
Total PFASs (rounded)	0	0	0	1.8	10	10

2.2.4 Consumer mixtures

Application

This diverse group includes the following applications (from the PFAS restriction proposal):

- Cleaners for glass, metal, ceramic, carpet and upholstery
- Waxes and polishes for e.g. furniture, floors and cars
- Floor polish removers
- Drycleaning products
- Dishwashing products as rinse aid
- Windscreen treatments for automobiles and windscreen wiper fluids
- Car care products
- Rain-repellent fluids in the aviation industry
- Anti-fog agents
- PTFE spray for lubrication of doors, locks, bike chains, motorcycles etc.
- Musical instruments: Lubricants for music instruments, guitar strings, in piano keys

Types of PFASs used

According to the PFAS restriction proposal, a variety of PFASs including fluorotelomer alcohols and ethoxylates, perfluoroalkylcarboxylic acids, perfluoroalkylethers, perfluoroalkanesulfonamide acetates and polymers such as PTFE are used in consumer mixtures for various technical functions, such as for achieving water and stain repellence and as wetting agents.

Production in Denmark

No specific information was encountered regarding any production in Denmark. However, the following entries in the Danish Product Registry may relate to this group of applications (WEA, 2023):

- Cleaning (<0.005 t PFAS/y)
- Consumers' manufacture of goods and services for own use, not specified elsewhere (<0.01 t PFAS/y)
- Consumers' manufacture of services for own use, not specified elsewhere (<0.1 t PFAS/y)

Quantities used

The PFAS restriction proposal cites Glüge et al. (2022) as follows: For the Scandinavian countries Norway, Denmark, Sweden and Finland it was estimated (using the SPIN database) that in a period of 17 years (2000 - 2017), 21 t PFASs were used in cleaning agents. Extrapolation from this figure to an annual tonnage for the entire population of the European Economic Area (EEA) results in an estimation of 20 t/y, mainly of non-polymer PFASs.

For use on/with musical instruments, the restriction proposal estimates an input of 1-10 t/y PFAS, and notes that the estimate is uncertain.

Scaling the EEA PFAS inputs to the Danish population, the inputs to Danish society were estimated in this study as shown in Table 22. Considering the uncertainties of both data sets, these estimates are in agreement with the aforementioned registrations in the Danish Product Registry (see above).

Table 22. Estimated consumption of PFASs in Denmark in consumer mixtures in 2021

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Cleaning agents	0	0	0.3	0.3
On musical instruments	0	0	0.08	0.08
Total	0	0	0.38	0.38

Trends in consumption and accumulation in society

According to the restriction proposal, no information on trends was available. Therefore, a growth rate of 0% is assumed.

Emission and distribution factors

The PFAS restriction proposal assumes, based on consultations and relevant standard exposure scenarios that 100% of the PFASs in cleaning agents and similar are released to wastewater (ERC 8A and ERC 8D; for widespread use of non-reactive processing aids which are not included into or onto articles). The same is the case for guitar strings, a significant fraction of the use for instruments, from which the PFASs are transferred to the fingers and subsequently washed off.

Estimated emissions to Danish society are therefore identical to the estimated consumption, as shown in Table 23.

Table 23. Estimated flows of PFASs to Danish society from consumer mixtures in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0	0	0	0	0	0
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0	0	0	0.38	0	0.38
Total PFASs (rounded)	0	0	0	0.38	0	0.38

2.2.5 Cosmetics

Application

According to the PFAS restriction proposal, PFASs are used intentionally in various categories of cosmetics functioning as, for instance, emulsifiers, antistatics, stabilizers, surfactants, film formers, viscosity regulators and solvents (ECHA, 2023, citing Pütz et al., 2022). Out of these, the most frequently occurring properties are for skin conditioning, film forming, solvent and surfactant. More details are provided below.

The PFAS restriction proposal distinguishes between the following cosmetic sub-product types:

- Skin care
- Toiletries
- Hair care
- Perfumes and fragrances
- Decorative cosmetics

However, the functions of the PFASs across these sub-products as described below.

Types of PFASs used

Table 24 shows the identified functions of the most frequently used PFASs in cosmetics (from the PFAS restriction proposal).

Table 24. Functions of some frequently used PFASs in cosmetics (source: ECHA, 2023)

PFAS	PFAS category	Identified properties according to CosIng*
PTFE	Polymeric PFASs	Bulking
C9-15 fluoroalcohol phosphate a)	PFAAs and precursors	Skin conditioning
Perfluorodecalin	PFAAs and precursors	Detangling
Perfluorooctyl triethoxysilane b)	PFAAs and precursors	Skin conditioning
Perfluorononyl dimethicone a)	PFAAs and precursors	Solvent
Polyperfluoromethylisopropyl ether	Polymeric PFASs	Binding
Octafluoropentyl methacrylate	PFAAs and precursors	Skin conditioning
Acetyl trifluoromethylphenyl valylglycine	PFAAs and precursors	Skin conditioning
Methyl perfluorobutyl ether	PFAAs and precursors	Binding

Notes: a) Covered by the PFOA restriction in POPs and the C9-C14 PFCAs restriction in REACH. b) Covered by the (3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl) silanetriol and TDFAs restriction in REACH. * Cosing: The cosmetic ingredient database.

Production in Denmark

Production of cosmetics does take place in Denmark; however, no information was encountered regarding any production with PFASs in Denmark.

Quantities used

The PFAS restriction proposal states that on an overall basis, the market share of PFAS-containing cosmetics was 1.1-1.3% based on the product databases Kemiluppen and CosmEthics. An analysis of the market share of PFAS-containing products revealed that most occurred in the decorative cosmetics product category (3.7%), followed by skin care, hair care and toiletries (0.78, 0.65 and 0.27% respectively). The occurrence of PFASs in perfumes and fragrances was negligible at 0.03% (Based on cosmEthics).

Based on KEMI (2021), the PFAS restriction proposal estimated PFAS consumption by subproduct type as shown in Table 25, noting that a disaggregation in PFAS types was not possible. However, as indicated above, the vast majority of PFASs used seem to be PFAAs and precursors; the total input is therefore categorized as such in this study.

Table 25. Quantities of PFASs used in cosmetics by application sub-category and key substance groups in the EEA in 2020 (mid-points; ECHA, 2023).

	Consumption with end products, t/y (midpoint estimate)			
Sub use	Polymeric PFASs	TFA related PFASs	PFAAs and precursors	Total PFASs
Skin Care	*	*	0.014 - 49.9	0.014 - 49.9
Toiletries	*	*	0.002 - 2.5	0.002 - 2.5
Hair Care	*	*	0.003 - 4.6	0.003 - 4.6
Decorative Cosmetics	*	*	0.01 -7.1	0.01 -7.1
Total	*	*	0.028 - 64.2	0.028 - 64.2

* Parts of the tonnages mentioned may be polymeric or TFA related PFAS, but these could not be quantified separately.

Scaling the EEA consumption to the Danish population results in the consumption estimates shown in Table 26.

Table 26. Estimated consumption of PFASs in Denmark with cosmetics in 2021

	Consumption with end products, t/y			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and pre-cursors**	**Total PFASs**
Skin Care	*	0	0.3	0.3
Toiletries	*	0	0.02	0.02
Hair Care	*	0	0.03	0.03
Decorative Cosmetics	*	0	0.05	0.05
Total	*	0	0.4	0.4

* Parts of the tonnages mentioned may be polymeric PFAS, but these could not be quantified separately based on data from the PFAS restriction proposal.

Trends in consumption and accumulation in society

According to the PFAS restriction proposal, a stable market is foreseen. This prediction is based on historic trends where there was no growth in market value in real terms in a three-year period ending in 2019. As such, a growth rate of 0% is assumed.

Emission and distribution factors

The PFAS restriction proposal assumes, as a worst-case scenario, that all cosmetics amounts used are released to sewage.

In reality, certain minor fractions go to waste treatment, for example from unused cosmetics residues in containers and from decorative cosmetics wiped of the skin and disposed with the wiping material (typically cotton rounds or similar).

As no data are available on the distribution between wastewater and waste treatment, and wastewater is deemed the dominant release pathway, the annual outputs to wastewater are assumed equal to the annual inputs of PFASs in cosmetics to the Danish society, as shown in Table 27.

Table 27. Estimated flows of PFASs to Danish society from cosmetics in 2021

Group of PFASs	Total outputs, t/y					
	Air	**Soil**	**Surface water**	**Sewage**	**Waste treatment**	**Total out-puts (rounded)**
Polymeric PFASs	0	0	0	*	0	0
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0	0	0	0.4	0	0.4
Total PFASs (rounded)	0	0	0	0.4	0	0.4

* Parts of the tonnages mentioned may be polymeric PFAS, but these could not be quantified separately based on data from the PFAS restriction proposal.

2.2.6 Ski wax

Application

Ski wax is used for two purposes: to make the skis glide better (all skiing) and to get a desired grip to the snow in the middle of the ski, allowing for a better kick-back in cross-country skiing. Due to the climate, skiing in Denmark is not very widespread, and the skiing actually taking place is primarily cross-country skiing, meaning with both ski waxing functions. On the other hand, many Danes go skiing abroad (to the Alps, Norway and Sweden), and most are deemed to do downhill skiing, often with skis rented and waxed at the ski venue. Therefore, most of the

ski wax purchased in Denmark may likely be released to the environment abroad. However, as the amounts of PFASs used with ski wax are minimal, this use is treated in less detail here than other PFAS uses, and consumption and emissions are estimates on similar *per capita* basis as in the EEA on average.

Types of PFASs used

According to the PFAS restriction proposal, the main PFASs used in ski waxes are perfluoroalkanes and semi-fluorinated alkanes. The semi-fluorinated alkanes used are di-block and tri-block semi-fluorinated n-alkanes (SFAs) and are typically mixed with normal paraffins in the formulations of ski waxes. Fluoropolymers are also used in some waxes.

The contents of PFASs in individual ski waxes vary depending on price and consumer preferences. High-priced ski waxes are typically either high in PFASs for optimal performance or are based on natural waxes that are assumed to be more eco-friendly.

Production in Denmark

The production of ski wax with PFASs is highly unlikely in Denmark.

Quantities used

The PFAS restriction proposal assumes an input of PFASs to ski waxes of 1.6 t/y to ski waxes produced in the EEA in 2020.

Assuming a similar *per capita* consumption in Denmark, the annual input to Denmark is estimated as shown in Table 28, dominated by non-polymeric PFAS, though polymeric PFASs use cannot be ruled out.

Table 28. Estimated consumption of PFASs in Denmark ski wax in 2021

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Ski wax total		0	0.02	0.02

Trends in consumption and accumulation in society

According to the restriction proposal, the use of PFAS-containing ski waxes peaked around 2000 and has decreased to about a third of the 2000 estimates at present. Because of the low amounts, any accumulation in society of PFASs in ski wax is ignored in this study.

Emission and distribution factors

The PFAS restriction proposal estimates output factors based on detailed studies as follows: air: 3%, surface water: 28%, soil: 28%, and waste treatment 41%.

The estimated emissions to Danish society are therefore estimated as shown in Table 23.

Table 29. Estimated flows of PFAS to Danish society from ski wax in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0	0	0	0	0	0
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0.001	0.006	0.006	0	0.008	0.02
Total PFASs (rounded)	0.001	0.006	0.006	0	0.008	0.02

2.2.7 Medical devices

Application and types of PFASs used

Based on the PFAS restriction proposal, Table 30 summarises the main PFASs uses in medical devices.

Table 30. Main PFASs used in medical devices, by sub-use

Sub use	Main PFASs used	PFAS main types
Fluorinated meshes and wound treatment	Porous membranes containing ePTFE (expanded PTFE) or PVDF are used as mesh material or patches, because they reduce adhesion, one of the possible complications in hernia reinforcement. Also, part of medical and silicone tapes and wound dressings rely on PFPE-enabled release liners for their function. Surgical staples leverage a PBSF surfactant as a coating to approximate skin for surgical or acute wounds.	Polymeric PFASs
Medical textiles	Fluorotelomers. Note also coverage of Section 2.2.1	
Medical implants	Polymers are used for medical implants, with PTFE being the most abundant fluoropolymer. Fluoropolymers such as PVDF and FEP are also used as biocompatible materials.	Polymeric PFASs
Tubes and catheters	Catheter tubes are usually made of ePTFE for smooth surface and minimizes the need to use force. Due to lower physical characteristics of ePTFE, FEP is used in some cases, for example for connections.	Polymeric PFASs
Coatings	Coatings have many uses in medical devices due to their inertness to various materials, including human tissue and medicals. Main coatings used are reported to be SF-coat-AS-20280 (2414599-48-9), SF-coat-SFE-X008 (441049-46-2), AsahiGuard-AG-E082 (746622-86-6), ETFE (25038-71-5), PTFE (9002-84-0), PCTFE (9002-83-9)	Polymeric PFASs or FAAs and precursors
Cleaning and heat transfer: engineered fluids	Perfluorinated “engineered fluids” (not further specified). These can be used to deposit a wide variety of coatings, as solvents for chemical reactions, as inert media and in microfluidic applications. The mentioned solvents are intended for industrial use only and are not intended for use as a medical device or drug.	TFA related PFASs
Sterilization gases	A mixture of 12% by weight ethylene oxide and 88% chlorofluorocarbon-12 (CFC-12) (12/88) has previously been widely used to make non-flammable sterilization gases.	TFA related PFASs
Packaging	PFAS, especially fluoropolymers, are widely used in medical packaging applications, for example ETFE, PTFE and PCTFE (the latter for consumer pharmaceuticals and similar). Some medical devises are packed in fluoropolymers packaging that allow the penetration of ethylene oxide for sterilisation.	Polymeric PFASs
Electronic equipment	See section 2.2.9	
Diagnostic laboratory testing	PTFE.	Polymeric PFASs

Sub use	Main PFASs used	PFAS main types
Metered Dose Inhalers (MDI)	Fluorinated gases (mainly HFC-134a, HFC-227ea). Arrowhead substances are mainly TFA and/or other PFAAs.	TFA related PFASs
Others	PTFE for contact lenses	Polymeric PFASs

Production in Denmark

Companies engaged in production of medical devices are present in Denmark. No attempt have been made to collect information regarding production with PFASs in the country.

Quantities used

The PFAS restriction proposal sums up the quantities of PFASs used as shown in Table 31, noting that amounts may likely be underestimated due to lack of data from the complex supply chain. The split between industrial use in the production of the devices and use in the final devices is not indicated for the PFAAs and precursors and the polymeric PFASs. From the description of the uses, the impression is that the majority is used in the industrial production of the devices.

Table 31. Estimated consumption of PFASs in the EEA medical devices in 2020 (ECHA, 2023)

	Consumption with end products, t/y (midpoint estimate)			
Sub use	Polymeric PFASs	TFA related PFASs	PFAAs and precursors	Total PFASs
Propellants in MDI	0	160 - 6,000	0	160 - 6,000
Fluorinated gases used in industrial processes related to medical application (for instance medical lasers)	0	20,000 - 40,000	2	20,000 - 40,000
Coatings and surfactants in medical devices	3,233 - 12,032	0	800	4,033 - 12,832
Other applications (e.g. heat transfer fluids and fluids for cleaning)	0	0	477 - 2,692	477 - 2,692
Total for all medical device uses categories	3,233 - 12,032	21,160 - 46,000	1,279 - 3,495	24,672- 61,527

Specifically for MDI (metered dose inhalers), consumption and emissions are quantified in the report “Danish consumption and emission of F-gases in 2021” (Poulsen, 2023). The MDI PFAS consumption estimate from Poulsen (2023) is 6.7 t/y, about 1/3 of the estimate resulting from a *per capita* scaling of the EEA consumption. The same main PFAS propellants contribute to the two input estimates; this may indicate that PFAS-propelled MDIs are used to a lesser degree in Denmark.

As regards “Fluorinated gases used in industrial processes related to medical application (for instance medical lasers)”, this use is not singled out as a specific application by Poulsen (2023). However, as it is assumed to have been covered implicitly in Poulsen (2023), in this study, this use is considered to be covered in section 2.2.15 on the application of fluorinated gases.

Assuming a similar *per capita* consumption in Denmark and omitting the use of fluorinated gases used in medico-industry (covered in section 2.2.15), the consumption of PFASs in production and use of medical devices in Denmark can be estimated as shown in Table 32. The

consumption of MDI is included in section 2.2.15 with specific Danish consumption figures. As indicated above, the impression is that the majority of the PFAAs and precursors are used in the industrial production of the devices, and it is highly uncertain to what extent such production processes takes place in Denmark.

Table 32. Estimated consumption of PFAS in Denmark in medical devices in 2021

	Consumption with end products, t/y			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Propellants in MDI	0	*	0	*
Fluorinated gases used in industrial processes related to medical application (for instance medical lasers)	0	*	0.03	0
Coatings and surfactants in medical devices	100	0	10	110
Other applications (e.g. heat)	0	0	20	20
Total for all medical device uses categories	100	0	30	130

* Included in section 2.2.15 on application of fluorinated gases.

Trends in consumption and accumulation in society

The PFAS restriction proposal assumes an annual growth rate of 3.4%, but as the lifetimes of the main volumes (coatings and surfactants in medical devices) are deemed short, accumulation in the Danish society is considered negligible in this study.

Emission and distribution factors

In the PFAS restriction proposal, emission factors were based on consultant expertise (not on ERCs for this use) and were estimated as follows (where flows to waste treatment are not included). The restriction proposal notes that these emission factors are associated with substantial uncertainty:

- 10% for non-polymer PFASs in industrial processes (heat transfer agents, specialty cleaners, and end-products); not further specified. Assumed in this study to be 20% by volatile precursors to air, and 80% to wastewater via cleaning procedures.
- 1% for PFAS polymers (by wear and tear); assumed to be emissions to wastewater via cleaning procedures in this study.

Applying the above emission factors, the estimated emissions to the Danish society are as shown in Table 33, except for emissions from MDI (7 t/y under TFA related PFASs) which are estimates from the Danish F-gas report (Poulsen, 2023).

The PFAS restriction proposal does not distinguish between the life cycle phases. However, from the overall description of uses, the main releases would be from the production of the devices and not from their use in the health sector.

Table 33. Estimated flows of PFASs to Danish society from medical devices in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0	0	0	1.0	100	100
TFA related PFASs *	0	0	0	0	0	0
PFAAs and precursors	1	0	0	2.4	27.0	30
Total PFASs (rounded)	1	0	0	3	130	130

* Included in section 2.2.15 on application of fluorinated gases.

2.2.8 Transport

Application and types of PFASs used

According to the PFAS restriction proposal, products and articles used in the transportation sector containing PFASs are very diverse. The transportation sector encompasses the sub-sectors automotive, maritime, aviation, and railway.

The PFAS restriction proposal lists the following sub-uses and the functions and types of PFASs used (Table 34).

Table 34. Uses, functions and types of PFASs in the transport sector

Sub use	Main PFASs used and their function	PFAS main types
Body-, hull-, and fuselage construction	PFASs and especially polymeric PFASs are important for body-, hull-, and fuselage construction e.g. as industrial feedstock or as functional chemicals. Examples are: • Release film for mould components for the manufacture of plastic parts (e.g. PTFE, ETFE) • Surface tension modifiers in plating processes during the body-, hull-, or fuselage construction (minimizing the generation of chromium mists) • Flame/fire resistance • Inner walls and other surfaces in planes (for hygiene)	Polymeric PFASs
Sealing applications (see also separate section)	Polymeric PFASs (e.g. fluoroelastomers such as FKM or fluoropolymers such as PTFE) are used to produce seals for various parts of transportation vehicles. Most of these parts belong to the propulsion system. Sealing applications with polymeric PFASs (e.g. PTFE) are likely the largest subgroup of PFASs applications in transportation: 60% or more of the fluoroelastomers produced are used in sealing applications in the transportation sector.	Polymeric PFASs
Combustion engine system	Besides sealing and coating applications, there are some special applications, e.g. non-woven textiles covering the engine bay area as acoustic insulation inside the vehicle engine compartment (treated with low molecular PFASs as well as with polymeric PFASs to achieve oil repellence and high temperature resistance and make them non-flammable).	Polymeric PFASs
Lubricants (see also separate section)	Lubricants based on polymeric PFASs (e.g. PTFE, PFPE) are used in transportation vehicles, mainly to reduce friction in a wide range of applications and over a wide range of temperatures.	Polymeric PFASs
Hydraulic fluids	PFASs are used in hydraulic fluids e.g. as corrosion inhibitors.	
Electrical engineering and information technology (see also separate section)	As for electronics and electrical parts in general (see other section), PFASs play a part in such components in transport means, for example: • Computer-based systems • Data transmission in optical fibres made of fluoropolymers	Polymeric PFASs

Sub use	Main PFASs used and their function	PFAS main types
	• Batteries: Fluorinated polymer seals (often PVDF) and battery coolants based on fluorinated gases. Polymeric PFASs are used as coating for the separator film in Li-Ion batteries. • Fuel cells: Perfluoropolymeric sulfonyl fluoride ionomers act as a binder and proton conductor in the catalyst layers in fuel cells. PTFE is part of the gas diffusion layer controlling the water management of a fuel cell. • Other electricity-based processes specific to the transportation sector (e.g. disinfection of ballast water using UV-radiation).	
Coating and finishes	Polymeric PFASs are used in the transportation sector for coating applications e.g. PTFE, ETFE, PFA, or FEVE. Coating of, among others: Cables, fuel filters, protection of paint surfaces, insulation, windshield glass screen dirt-repellence, windshield wipers, brake pads, textiles. Road signs and beaded retroreflective signal colours on roads. Turbulence reduction on aircraft blades. Antifouling of ships. PTFE, ETFE or PFA are used for lubrication free low-friction bearings in various rotating parts.	Polymeric PFASs
HVACR-systems in transportation vehicles (see also separate section)	Functional fluids of heating, ventilation, air conditioning and refrigeration (HVACR)-systems. Special heat transfer fluids (e.g. methoxyheptafluoropropanes) for the immersion-cooling/heating of electronic equipment. High Efficiency Particulate Air (HEPA) filters for AC-systems in planes and vehicles (PTFE).	TFA related PFASs PFAAs and precursors
Lifesaving and fire protection	Airbags, seatbelts (retractor mechanism only), life jackets, life rafts, etc.	Polymeric PFASs
Other uses related to transportation	Traffic sign coatings, adhesive tape on flights, flotation fluids in gyroscopes, adhesiveness and weatherability in wheel balancing weights, cover sheets/wrapping for new vehicles.	Polymeric PFASs

Production in Denmark

No specific information was encountered regarding any production with PFASs in this sector in Denmark. However, the following entries in the Danish Product Registry may relate to this group of applications (WEA, 2023):

- Maintenance and repair of motor vehicles (<13 t PFAS/y; probably mainly 1,1,1,2-tretrafluorethane refrigerant covered in section 2.2.15, but also PTFE)

There are also other, very generalised, sector entries that could potentially contribute to the transport sector. See all registered sectors in Appendix 3.

Quantities used

The PFAS restriction proposal can only account for some of the uses as regards tonnages used, and it is noted that the data available are likely underestimates of actual tonnages as they only cover parts of the uses. The available information on PFAS consumption for the transport sector is summarized in Table 35. PFAS gases used in transport are mentioned here, but are otherwise accounted for in section 2.2.15 on PFAS gases. Of the estimated 13,232 t/y, ca. 12,222 t/y is used in the EEA in newly manufactured road vehicles for passenger comfort and ca. 1,010 t/y is added into newly manufactured products for transport refrigeration.

Table 35. Reported consumption of PFASs in the EEA in the transport sector in 2020 (ECHA, 2023)

	Consumption with end products, t/y (low - high estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs ***	**PFAAs and precursors ***	**Total PFASs**
Road vehicles	6,410 - 14,653	13,232	100 - 1,000	19,742 - 28,885
Other transportation uses 3)		10 - 100		10 - 100
Total (rounded)	6,410 - 14,653	13,287	100 - 1,000	19,752 - 28,985

* Additional side-chain-fluorinated polymers, etc. are known to be used, but data are unavailable.

** Gas uses for HVRAC etc. are covered in section 2.2.15. Several other uses are known, but no data for these are available.

Assuming similar *per capita* consumption in Denmark, the (partial) consumption of PFASs in the transport sector can be estimated as shown in Table 36. Note that these numbers likely represent an underestimation, as explained above for the EEA; as well, the contributions from PFAS gases were omitted here, as they are counted under section 2.2.15 on PFAS gases.

Table 36. Estimated consumption of PFASs in Denmark from transport in 2021 (data are missing for some applications)

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs ***	**PFAAs and precursors**	**Total PFASs**
Road vehicles	140	0	7	150
Other transportation uses	0	0	0	0
Total (rounded)	140	0	7	150

* Application is covered by section 2.2.15 on application of fluorinated gases.

Trends in consumption and accumulation in society

According to the restriction proposal, minor growth is expected (1% pa), and accumulation in society is therefore considered negligible in this study.

Emission and distribution factors

The PFAS restriction proposal's estimation of emissions addresses polymeric PFASs in road vehicles only and is noted as underestimating actual emissions. The emission factors shown in Table 37 were used.

Table 37. Emission factors used in the PFAS restriction proposal

	ERC used	Air (%)	Water (%)	Soil (%)
Outdoor use (50% of input)	10a	0.05	3.2	3.2
Indoor use (50% of input)	11a	0.05	0.05	0

Assuming a similar output distribution, the estimated emissions to Danish society can be calculated as shown in Table 38. Note that emissions from gases are assigned to "Application of fluorinated gasses" in section 2.2.15. As mentioned, the given tonnages should be considered to underestimate emissions.

Table 38. Estimated minimum flows of PFASs to Danish society from transport in 2021

Group of PFASs	Estimated outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0.1	2.2	0	2.3	140	140
TFA related PFASs *	0	0	0	0	0	0
PFAAs and precursors	0.0	0.1	0	0.1	7	7
Total PFASs	0.1	2	0	2	147	147

* Emissions are covered by section 2.2.15 on application of fluorinated gases.

2.2.9 Electronics and semiconductors

Application and types of PFASs used

According to the PFAS restriction proposal, PFASs are used for a large variety of purposes in both the manufacture of semi-conductors and in electronic products. The focus in this study is on PFASs in electronic products; for further details on manufacture of semi-conductors, see the PFAS restriction proposal (ECHA, 2023). The PFAS restriction proposal lists the following sub-uses of PFASs in electronics in Table 39.

Table 39. Sub-uses of PFASs in electronics (source: ECHA, 2023)

Sub-use	Examples of PFASs used	PFAS main types
Wires and cables (heating cables, coaxial cables)	PTFE, PFA, ETFE, FEP, FEPM, PFPE	Polymeric PFASs
Coating of electronic components / membranes in many internal and external parts of electronics	PTFE, FEP and PFA, 2-(perfluorohexyl)ethyl acrylate, 2-(Difluoromethoxymethyl)-1,1,1,2,3,3,3-heptafluoro-propane, 1,1,1,2,2,3,3,4,4-Nonafluoro-4-methoxy-butane, PFHxA	Polymeric PFASs PFAAs and precursors
Electronic components such as: Vent filters, Sound-permeable membrane, Air filter, Tactile switch components, Printed circuit boards, Antennas and membranes, Liquid crystal displays (LCD), Organic light-emitting diode (OLED), Optical fibres (Polymer optical fibre), Rod lenses	PTFE, PFA, Fluoropolymers, F-PMMA. In LCDs/OLEDs: Non-polymeric PFASs, PFHxA.	Polymeric PFASs PFAAs and precursors
Anti-drip agent	PTFE, 1-Propene, 1,1,2,3,3,3-hexafluoro-, polymer with 1,1-difluoroethene and tetrafluoroethene	PFAAs and precursors
Fire protection fluid	1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone	PFAAs and precursors
Heat transfer fluids (covered in separate section)	(Z)-1,1,1,4,4,4-Hexafluoro-2-buten; Butane, 1-ethoxy-1,1,2,2,3,3,4,4,4-nonafluoro-, 2,3,3,4,4-pentafluoro-5-methoxy-2,5-bis[1,2,2,2-tetrafluoro-1-(trifluoromethyl)ethyl]tetrahydrofuran, Perfluamine, 1,1,1,2,2,4,5,5,5-nonafluoro-4-(trifluoromethyl)-3-pentanone, 2-(Trifluoromethyl)-3-ethoxydodecafluorohexane,	PFAAs and precursors TFA related PFASs
	Reaction mass of 1,1,2,2,3,3,4,4,4-nonafluoro-N,N-bis(nonafluorobutyl)butan-1-amine and 1,1,2,2,3,3,4,4,4-nonafluoro-N-[1,1,2,3,3-hexafluoro-2- (trifluoromethyl)propyl]-N-(1,1,2,2,3,3,4,4,4-nonafluorobutyl)butan-1-amine.	Polymeric PFASs
Sealing for electronic components	Fluorinated gases	TFA related PFASs
Solvent	No examples mentioned in ECHA (2023)	

Aerosol/ Solvent cleaning of electronics components	Fluorinated gases, 2-(Difluoromethoxymethyl)-1,1,1,2,3,3,3-heptafluoro-propane, 1,1,1,2,2,3,4,5,5,5-decafluoro-3-methoxy-4-(trifluoromethyl)pentane	TFA related PFASs PFAAs and precursors
Lubricants (solids, oils; covered in separate section)	PTFE, PFA, ETFE, PFPE, Tetrabutylphosphonium Perfluorobutylsulfonate, PFPEs and PCTFE base oils, Z)-1,1,1,4,4,4-Hexafluoro-buten, Butane, 1,1,1,2,2,3,3,4,4-nonafluoro-4-methoxy-, Butane, 1-ethoxy-1,1,2,2,3,3,4,4,4-nonafluoro-	Polymeric PFASs PFAAs and precursors

Production in Denmark

To our knowledge, large-scale manufacture of semiconductors is absent in Denmark (however, development of new types of semiconductors does occur in Denmark). As regards other uses of PFASs in the sector, no specific information was encountered regarding production with PFASs in this sector in Denmark. However, the following entries in the Danish Product Registry may relate to this group of applications (WEA, 2023):

- Production of electronic components, printed circuit boards (PCBs), etc. (0.1 t PFAS/y)
- Manufacture of electrical equipment (<1 t PFAS/y)

Quantities used

The PFAS restriction proposal only provides summarized information on PFAS quantities used in the EEA, divided by substances key groups, but not by sub-use. The numbers given in Table 40 therefore include manufacture of semiconductors. However, it is not clear if PFASs in electronics imported from outside the EEA are included in the numbers.

Table 40. Estimated consumption of PFASs in the electronics and semiconductors industry in the EEA in 2020 (no separation of lifecycle phases is given in the source: ECHA: 2023)

	Consumption with end products, t/y (low - high estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Total (electronics + manufacture of semiconductors)	1,560 - 4,615	140	841 - 1,549	2,541 - 6,304

A *per capita* scaling of the EEA input given above to Danish conditions may overestimate consumption, as large-scale manufacture of semiconductors is absent in Denmark (however, development of new types of semiconductors does occur in Denmark). However, in the case that PFASs in electronics imported from outside the EEA are not included in the EEA inputs of PFAS, this could result in an underestimation. *Per capita* scaling estimates are, however, given for Denmark in Table 41 as no other data are available.

Table 41. Estimated consumption of PFASs in Denmark with electronic products and semiconductors in 2021

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Total (electronics + manufacture of semiconductors)	40	0 *	15	55

* Included in section 2.2.15.

Trends in consumption and accumulation in society

According to the restriction proposal, for PFASs used in electronics, a growth rate of 10% per year is assumed as the general electronics industry (including semiconductors) is experiencing growth. Assuming an average lifetime of large volume electronics of 8 years (from being marketed, via any re-use, to being disposed of), the estimated PFAS output in 2021 would be on the order of around 50% of the inputs estimated above in Table 41 for 2021, with a 10% annual growth rate.

A growth rate of 10% means that, in the case that restrictions of PFASs are not implemented, the amounts to be handled in waste treatment would increase significantly in future years.

Emission and distribution factors

As the PFAS restriction proposal does not disclose the distribution between PFAS inputs to manufacture and end products, the emission factors used cannot be transferred directly to Danish conditions, dominated by emissions from end products. The PFAS restriction proposal does, however, show estimated emissions form the use phase of the end products. Therefore, emissions to Danish society were derived by using a population-based scaling of the given emission estimates for the EEA to the use phase, in combination with the assumption of a 50/50 distribution of non-waste emissions between air and wastewater (indoor use was assumed to dominate). However, flows to waste treatment were calculated as total PFAS inputs from both lifecycle phases minus emissions from both phases, which may deviate from actual flows to waste.

Table 42. Calculated emissions to the environment in the EEA from the use phase of electronics (ECHA, 2023)

	Emissions from the use stage, t/y
PFAAs and precursors	0.3 - 1.0
Polymeric PFASs	2 - 4

The emission estimate prepared by ECHA applies a one-compartment model, i.e., the releases are not divided into emissions to air, soil, and water. The ERCs and one-compartment model emission factor are shown in the table below. In addition, the table show the emissions factors used in this study for the distribution of outputs to air, sewage and solid waste. The distribution between ionic and non-ionic non-polymer PFASs is not reported in the restriction proposal; for the distribution applied in this study, a 50/50 split is assumed.

Table 43. Emission factors used for estimations of releases from the use phase of electronics

Type of PFASs	ERCs	Emissions, one compartment model, %	Emission factors applied in this study		
			Air %	Sewage %	Solid waste %
Polymeric PFASs	11A	0.1		0.1	99.9
Ionic non-polymer PFASs	11A	0.1		0.1	99.9
Non-ionic non-polymer PFASs	9A	5	5		95

The results are shown in shown in Table 44.

Table 44. Estimated flows of PFASs to Danish society from electronics and semiconductors in 2021

Group of PFASs	End-product outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0	0	0	0.04	19	19
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0.01	0	0	0.0002	4	4
Total PFASs (rounded)	0.01	0	0	0.04	23	23

2.2.10 Energy sector

Applications and types of PFASs used

The PFAS restriction proposal lists the functions of PFASs in the energy sector shown in Table 45 along with examples of PFASs used.

Table 45. Sub-uses and application and types of PFASs in the energy sector

Sub use	Application	Main PFASs used	PFAS main types
Solar collectors	Bearings of tracking systems	PTFE	Polymeric PFASs
Photovoltaic cells	Front and back sheets of PV modules	PVDF, ETFE, FEVE, PFPE	Polymeric PFASs
Wind turbines (partly covered in other sections on construction materials and lubricants, resp.)	Coating on blades and towers; cables. lubricants	FEVE, ETFE, perfluorobutane sulphonamide, PTFE	Polymeric PFASs PFAAs and precursors
Coal-fired power plants	Heat exchanger tubing, filters	PTFE, Fluoropolymers	Polymeric PFASs
Nuclear power plants	Gasket materials	PTFE	Polymeric PFASs
PEM fuel cells /PEM electrolyzer (covered in other section)	Membrane electrode assemblies (MEA); Gas Diffusion Layer (GDL)/Microporous layer, Gaskets, sealant, membranes	PTFE, Perfluoroalkane sulfonic acids (PFSA) or perfluoroalkylether sulfonic acids (PFAE) ionomers, fluoroelastomers, other fluoropolymers, PFSA ionomer	Polymeric PFASs
Lithium-ion batteries	Seals, electrode binders, separator films/coatings, electrolyte additives, thermal management pack/module	Fluoroelastomer, PVDF	Polymeric PFASs
Rechargeable batteries	Battery fluid, compounds for separator films, binder		Polymeric PFASs PFAAs and precursors

Sub use	Application	Main PFASs used	PFAS main types
Flow batteries	Ionomer membranes Ion exchange membrane	Fluoropolymers	Polymeric PFASs
Electrolysis technologies (not PEM)	Equipment: gaskets, tubes, inline of pipes/tanks for large scale hydrogen production, etc.	Polymeric PFASs: PTFE, FKM, PVDF, TFM (chemically modified PTFE), FEP, ECTFE, PFA, PFPE	Polymeric PFASs
Oil and gas applications (covered in other section)	Gaskets, tubes, inline of pipes/tanks. Wires and capacitors.		Polymeric PFASs PFAAs and precursors
Switchgear Power Transmission Technologies Used in conversion of electric power (AC to DC)		Fluoropolymers; PTFE, PVDF. Non-polymeric PFASs; PFBS, C4-FN and C5-FK	Polymeric PFASs PFAAs and precursors

Production in Denmark

The production of some energy-related products does take place in Denmark, including wind turbines. There are indications that significant use of PFASs takes place in general manufacturing in Denmark. However, no information was encountered on whether PFASs are used specifically in production in this sector in Denmark. It is notable that the following entries in the Danish Product Registry may relate to this group of applications (WEA, 2023):

- Manufacture of electrical equipment (<1 t PFAS/y)
- Electrical installation, plumbing and other building installation activity (<1 t PFAS/y, probably mainly PTFE)
- Manufacture of machines for general purposes (<1 t PFAS/y)
- Manufacture of other machines for general purposes (<13 t PFAS/y)

Quantities used

The PFAS restriction proposal states that according to stakeholders, the main polymeric PFASs used in the energy industry are PTFE, PFA and a PFSA-ionomer, which account for 65%, 14% and 5% of the total fluorinated polymer use, respectively.

The PFAS restriction proposal only provides summarized information on PFAS quantities used in the EEA, divided by substances key groups, but not by sub-use. The numbers given in Table 46 therefore include both manufacture of products in the energy sector and the use phase of the same products. Of the PFAAs and precursors, the side-chain fluorinated polymers are estimated to account for 40 - 41 t/y and the non-ionic C2-C3 substances account for ca. 233 t/y.

Table 46. Estimated consumption of PFASs in the energy sector in the EEA in 2020 (no separation of lifecycle phases is given in the source: ECHA: 2023)

	Consumption with end products, t/y (low - high estimate)			
Sub use	Polymeric PFASs	TFA related PFASs	PFAAs and precursors	Total PFASs
Total (electronics + manufacture of semiconductors)	2,592 - 2,920	0	293 - 294	2,884 - 3,214

A *per capita* scaling of the EEA input given above to Danish conditions may deviate somewhat from the real consumption, as manufacture of energy sector products may differ in Denmark from the EEA average. However, the production of some energy-related products does take

place in Denmark, including wind turbines. However, *per capita* scaling estimates are given for Denmark in Table 47 as no other data on PFAS consumption were available within the study framework.

Table 47. Estimated consumption of PFASs in Denmark with energy sector manufacture and products in 2021 (see text)

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and pre-cursors**	**Total PFASs**
Total (energy sector)	40	0	4	44

Trends in consumption and accumulation in society

According to the restriction proposal, for PFASs used in electronics, a growth rate of 10% per year is assumed, similar to the general energy products. As the majority of the emissions take place from manufacture (in 2021), for simplicity, the total outputs are considered equal to the inputs in 2021.

A growth rate of 10% means that, in the case that restrictions on PFASs are not implemented, the amounts to be handled in waste treatment would increase significantly in future years.

Emission and distribution factors

As the PFAS restriction proposal does not disclose the distribution between PFAS inputs to manufacture and end products, the emission factors used cannot be transferred directly to Danish conditions. The PFAS restriction proposal does, however, show estimated emissions distributed to manufacture and the use phase. Therefore, emissions to Danish society were derived by using a population-based scaling of the total emission estimates for the EEA (manufacture + production), in combination with an assumption of a 50/50 distribution of non-waste emissions between air and wastewater (indoor use; ERC 11a). Flows to waste treatment were calculated as relevant PFAS inputs minus emissions. The results are shown in shown in Table 48.

Table 48. Estimated flows of PFASs to Danish society from the energy sector in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0.09	0	0	0.09	20	20
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0.27	0	0	0.27	1	2
Total PFASs (rounded)	0.36	0	0	0.36	21	22

2.2.11 Construction products

Applications and types of PFASs used

The PFAS restriction proposal lists the sub-uses, applications and examples of PFASs used as summarised in Table 49, noting that there are some internal overlaps, as well as overlaps with uses covered in other sections of this report.

Table 49. Sub-uses and application and types of PFASs in construction products

Sub use	Application	Main PFASs used	Main PFAS types
Roofing	Architectural and weatherproofing membranes	Polymeric PFASs e.g. PTFE, ETFE, FEP, PVDF Non-polymeric PFASs e.g. PBSF	Polymeric PFASs PFAAs and precursors
Wires and cables (covered under electronics)	Electrical insulation, gaskets	PTFE, PCTFE, ETFE, FEP, PVDF	Polymeric PFASs
Skidways	Construction works	PTFE	Polymeric PFASs
Construction bearings	Bridge bearings	Polymeric PFASs e.g. PTFE, PCTFE, ETFE, PVDF, FKM	Polymeric PFASs
Sealings and adhesives	Sealing of porous materials such as tiles and concrete indoors and outdoors. Sealing of pipe connections (water pipes, etc.)	Polymeric PFASs e.g. PTFE, PCTFE, ETFE, PVDF, FKM	Polymeric PFASs
	Adhesives for tiles, flooring, drywall, etc., and joint/gap sealants (caulks)	Polymeric PFASs e.g. fluoroelastomers, non-polymeric PFASs: fluorosurfactants	Polymeric PFASs PFAAs and precursors
Household applications	PTFE sealing tapes for water, ventilation and other pipes.	PTFE	Polymeric PFAS
	DIY sealants and adhesives	Polymeric PFASs e.g. PTFE and acrylate-, urethane- and siloxane-based side-chain fluorinated polymers, non-polymeric PFASs: e.g. fluorosurfactant	Polymeric PFASs PFAAs and precursors
Processing aids	Confidential manufacture uses; not present in end products	Non-polymeric PFASs (surfactant or solvent)	PFAAs and precursors
Polymer processing additives (PPA)	Additive/processing aids in thermoplastics (PE, PP, etc.)	Micro-powder PTFE, high-MW PTFE, PVDF, PFPE	Polymeric PFASs
Other polymer additives	Flame retardant. Antidrip additive. Antistatic agent to prevent the buildup of static electricity and dissipate the electric charge formed on the substrate	Polymeric PFASs e.g. PTFE, High-MW PTFE, PVDF, Non-polymeric PFASs: PFBS, PFHxS-Li+, pigments	Polymeric PFASs PFAAs and precursors
Foam blowing agents/additives (gasses covered in other section)	Foam insulation for e.g. polyurethane and other foam formulations	Fluorinated gases	TFA related PFASs

Sub use	Application	Main PFASs used	Main PFAS types
Wood sector	Wetting agent and sealers in coatings/paints/ varnishes/lacquers for wood substrate	Polymeric PFASs e.g. acrylate-, urethane- and siloxane-based side-chain fluorinated polymers, Non-polymeric PFAS: e.g. fluorosurfactants	Polymeric PFASs PFAAs and precursors
	Additive to Urea-formaldehyde resin in particleboard/chipboard/low-density fiberboard	Non-polymeric PFASs: fluorosurfactants	PFAAs and precursors
Glass sector	Surface coating of glass on buildings	Polymeric PFASs e.g. PTFE, PCTFE, Non-polymeric PFASs e.g. PBSF	Polymeric PFASs PFAAs and precursors
Metal industry/sector	Coating/painting of metal (including coil coating). Exterior and interior finishes and metal cladding.	Polymeric PFASs e.g. PTFE, FEP, PVDF, FEVE and silane/siloxane-based side-chain fluorinated polymers	Polymeric PFASs PFAAs and precursors
Outdoor electrical energy components (covered in other section)	Surface coatings of wind turbines and solar panels	See energy section	
Surface protection	Surface treatments of both absorbing and non-absorbing surfaces of building materials indoors and outdoors	Polymeric PFASs e.g. acrylate-, urethane- and silane/siloxane-based side-chain fluorinated polymers	Polymeric PFASs PFAAs and precursors
Architectural coatings and paints	Coating of surfaces of bridges and buildings, including anti-graffiti coating	Polymeric PFAS: PTFE, PVDF, ECTFE, FEVE, FEP, PFPE & acrylate- and silane/siloxane-based side-chain fluorinated polymers	Polymeric PFASs PFAAs and precursors
	Fluorinated additives in paints to achieve specific finishes and durability requirements on buildings and constructions	Polymeric PFASs e.g. PVDF, FEVE, ECTFE, PTFE, FEP, PFPEs, non-polymeric PFASs: surfactants, pigments	Polymeric PFASs PFAAs and precursors

Production in Denmark

There are indications of significant use of PFASs in general manufacturing in Denmark, and it is known that coating of metal (and possibly other materials) with PFASs does take place in the country. However, no information was encountered as to whether PFASs are used specifically in production in this sector in Denmark. It is notable that the following entries in the Danish Product Registry may relate to this group of applications (WEA, 2023):

- Surface treatment of metals, machine processing (<2 t PFAS/y)
- Construction of buildings (<0.04 t PFAS/y)
- Specialised building and construction (<0.02 t PFAS/y)
- Electrical installation, plumbing and other building installation activity (<1 t PFAS/y)
- Completion of buildings (<0.2 t PFAS/y; primarily PTFE and other fluoropolymers)

Quantities used

According to the PFAS restriction proposal, PTFE, ETFE and PVDF make up 97% of the reported total usage of fluoropolymers in building materials/construction products. The remaining 3% covers a range of fluoropolymers including fluoroelastomers such as FKM, FFKM and THV.

The PFAS restriction proposal only provides summarized information on PFAS quantities used in the EEA, divided by substances key groups, but not by sub-use, nor lifecycle phase. The numbers are given in Table 50. The PFAS restriction proposal cautions that some elements may be underestimated. Of the PFAAs and precursors, it is estimated that the side-chain fluorinated polymers account for 13 - 40 t/y.

Table 50. Estimated consumption of PFASs in the building materials/construction products in the EEA in 2020 (ECHA, 2023)

	Consumption with end products, t/y (low - high estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and pre-cursors**	**Total PFASs**
Building materials/con-struction products	5,254 - 10,320	0	987 - 2,405	5,241 - 12,725

A *per capita* scaling of the EEA input given above to Danish conditions produces the input estimates given for Denmark in Table 51.

Table 51. Estimated consumption of PFASs in Denmark with building materials/construction products in 2021 (see text)

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and pre-cursors**	**Total PFASs**
Building materials/con-struction products	90	0	22	112

Trends in consumption and accumulation in society

According to the restriction proposal, a moderate and declining growth rate is assumed. For fluoropolymers an annual real growth rate of 5% is assumed for the period 2020-2030. Due to the complexity of the use group, 2021 outputs are considered equal to 2021 inputs, in accordance with the PFAS restriction proposal.

Emission and distribution factors

The PFAS restriction proposal does not disclose the distribution between PFAS inputs to manufacture and end products; the emission factors used cannot be transferred directly to Danish conditions. The PFAS restriction proposal does, however, show estimated emissions distributed to manufacture and the use phase (with the majority of the emissions from the application phase). Therefore, total emissions to Danish society were derived by using a population-based scaling of the total emission estimates for the EEA (manufacture + production).

The main contributions to emissions come from application of products to which the PFAS restriction proposal applies ERC5 (possibly adjusted[20]) with total emissions 50%. According to ECHA (2016), ERC5 distributes emissions as follows: 49.5% to air, 49.5% to wastewater, and 1% to soil; this distribution was used for sub-allocation of the emissions to these environmental compartments (meaning for example 50%*49.5%=24.75% to air).

Flows to waste treatment were calculated as total PFAS inputs minus total emissions. For the EEA, emissions are sub-divided in the restriction proposal into articles and mixtures (such as paints, sealants), with the latter contributing about 95% of the emissions to air/water. For simplicity, this sub-division was not done in the context of this study.

The estimated emissions to Danish society are shown in Table 52.

[20] The PFAS restriction proposal quotes ERC5 non-waste emissions as 50% in total (with no explanation), whereas ECHA's guideline (2016) states emissions as being 50% to air, 50% to wastewater and 1% to soil. The latter values were adjusted to sum up to 100% for this study.

Table 52. Estimated flows of PFASs to Danish society from building materials/construction products in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	7	0	0	7	60	74
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	1	0	0	1	20	22
Total PFASs (rounded)	8	0	0	8	80	96

2.2.12 Lubricants

Application

The PFAS restriction proposal lists the applications of PFASs in lubricants as shown in Table 53, noting that the list is non-exhaustive. See the restriction proposal for more details.

The PFAS restriction proposal states that because of the wide range of properties, PFASs are widely used in lubricants, either as (part of) base oils (PFPEs and PCTFE), as a micro-powder additive (PTFE), or in very low volumes as other additives (wide range of PFASs) or as a solvent. Stakeholders report an estimated annual PFASs use of between 1,200 and 2,200 t/y (rounded numbers). Approximately one third of the PFASs used are (part of) base oils and two thirds are micro-powder additives.

Table 53. Sub-uses and application and types of PFASs in/as lubricants

Sub use	Application	Main PFASs used	Main PFAS types
Food sector (see also other section)	Moving parts in production, inside coating of metal food and beverages containers	PTFE, PFPE	Polymeric PFASs PFAAs and precursors
Aircraft, aerospace, military	Many moving parts, space suits	PTFE, PFPE (greases and oils)	Polymeric PFASs PFAAs and precursors
	Hydraulics and others	PTFE (oil)	PFAAs and precursors
Automotive	Moving parts, ESPs, electrical components, joints of automotive interior parts, exhaust system,	PTFE, PFPE (oils, greases)	Polymeric PFASs PFAAs and precursors
Trains	Valves, doors	PTFE, PFPE	Polymeric PFASs
Nuclear (see other section)	Moving parts, sealants, processing aids	PTFE, PFPE (oils, greases)	Polymeric PFASs PFAAs and precursors
Watch-making	Lubricants, greases	Polymeric PFASs + From C3 to C6 fluorinated chains	Polymeric PFASs PFAAs and precursors
Hearing aids	Moving parts in production	PTFE, PFPE	Polymeric PFASs
Electronics (see other section)	Circuit breakers, semi-conductor manufacturing, moving parts, instrument fill fluids	PTFE, PFPE, PCTFE (oil)	Polymeric PFASs PFAAs and precursors
Laboratory supplies, equipment, and instrumentation	Moving parts, surface coating	PTFE, PFPE, PCTFE (wax/grease, oil)	Polymeric PFASs PFAAs and precursors

Hospital equipment (see other section)	Moving parts, sealings, pressure gauges	PTFE, PFPE, PCTFE (grease, oil)	Polymeric PFASs PFAAs and precursors
Renewable energy (see other section)	Moving parts, sealings	PTFE, PFPE	Polymeric PFAS
Off-shore /oil-gas (see other section)	Moving parts, sealings	PTFE, PFPE, PCTFE	Polymeric PFASs PFAAs and precursors
Chemical industry	Sealings and moving parts in aggressive environments, processing aids	PTFE, PFPE, PCTFE (grease, oil)	Polymeric PFASs PFAAs and precursors
Bulk gas industry	Pumps and other moving parts	PCTFE (oil)	PFAAs and precursors
Metal-working and steel industries (see other section)	Cutting/drawing/forming oils, moving parts, etc.	PCTFE (oil, grease)	PFAAs and precursors
Water and wastewater treatment	Sealings compatible with chemical environment	PCTFE	PFAAs and precursors
Diving equipment	Seals, valves in oxygen-rich atmosphere	PTFE, PFPE, PCTFE (grease, oil)	Polymeric PFASs PFAAs and precursors
Handicap equipment (see other section)	Moving parts of wheelchairs, exoskeletons, etc.	PTFE	Polymeric PFAS
Paper production	Moving parts with aggressive chemicals	PTFE, PFPE, PCTFE	Polymeric PFASs PFAAs and precursors
Plastic/rubber parts manufacturing	Processing aids, slip-agents and moving parts	PTFE, PFPE, PCTFE	Polymeric PFASs PFAAs and precursors
Textiles production (see other section)	Moving parts	PFPE	Polymeric PFASs
Pharmaceutical industry	Lubricants in clean room applications	PFPE	Polymeric PFASs
Consumers (see other section)	Dry-film lubrication of bike chains, waterproof zippers	PTFE	Polymeric PFASs
Other sectors	Various applications with moving parts	PTFE, PFPE. Various PTFE and PFPE combinations	Polymeric PFASs

Types of PFASs used

The types of PFASs used in lubricants are shown in Table 53 above.

Production in Denmark

No specific information was encountered on whether PFASs are used in production in this sector in Denmark. However, the following entries in the Danish Product Registry may relate to this group of applications (WEA, 2023):

- Maintenance and repair of motor vehicles (<13 t PFAS/y, of which most is likely refrigerants; see gas section)
- Manufacture of machines and equipment, not specified elsewhere (<0.02 t PFAS/y)
- Manufacture of machines for general purposes (<1 t PFAS/y)
- Manufacture of other machines for general purposes (<19 t PFAS/y, of which most is likely refrigerants for other purposes)
- Other manufacturing, not specified elsewhere (<0.03 t PFAS/y)
- Repair of iron and metal goods, machines and equipment (<0.04 t PFAS/y)

Quantities used

The PFAS restriction proposal only provides summarized information on PFAS quantities used in the EEA, divided by substances key groups, but not by sub-use nor lifecycle phase. The numbers are given in Table 54. The PFAS restriction proposal cautions that as data are missing for some PFASs and net import inside articles and as mixtures are not included, the consumption tonnages may be underestimated. The solvents are indicated as fluorinated gases.

Table 54. Estimated consumption of PFASs in lubricants used in the EEA in 2020 (ECHA, 2023)

	Consumption with end products, t/y (low - high estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs ***	**PFAAs and precursors**	**Total PFASs**
PTFE micro-powder additive	800 - 1,200			800 - 1,200
PFPE base oil	300 - 800			300 - 800
Other additives than PTFE			1 - 10	1 -10
PFAS-based carrier and deposition solvents		35 - 75		35 - 75
PFAS-based cleaning solvents		35 - 75		35 - 75
Total	1,100 - 2,000	70 - 150	1 - 10	1,171 - 2,160

* Are included in section 2.2.15 on application of fluorinated gases,

A *per capita* scaling of the EEA input given above to Danish conditions produces the input estimates given for Denmark in Table 55.

Table 55. Estimated consumption of PFASs in Denmark with lubricants use in 2021 (see text)

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs ***	**PFAAs and precursors**	**Total PFASs**
PTFE micro-powder additive	13	0	0	13
PFPE base oil	7	0	0	7
Other lubricants and associated processing aids	0	0	0.1	0.1
Total (rounded)	20	0	0	20

* Are included in section 2.2.15 on application of fluorinated gases.

Trends in consumption and accumulation in society

According to the restriction proposal, a moderate and declining growth rate is assumed. A yearly real growth rate of 5% is assumed for the period 2020-2030. However, for simplicity, 2021 outputs are considered equal to 2021 inputs in this study, in accordance with the PFAS restriction proposal.

Emission and distribution factors

The PFAS restriction proposal does not disclose the distribution between PFAS inputs to production processes and end products, and consequently the emission factors used cannot be transferred directly to Danish conditions. The PFAS restriction proposal does, however, show

estimated emissions distributed to lifecycle phases (with the majority of the emissions from the application phase). Therefore, total emissions to Danish society were derived by using a population-based scaling of the total emission estimates for the EEA (processes + production).

The main contributions to emissions come from the use stage, and mainly from indoor sealed use, for which the PFAS restriction proposal applies ERC9A. According to ECHA (2016) ERC9A distributes emissions equally to air and wastewater, and this distribution was used to allocate emissions to these environmental compartments from polymers and other non-gas PFAS. Gas-like PFASs are used for cleaning prior to lubricating, and emissions of these were considered as going to air in this study.

Flows to waste treatment were calculated as total PFAS inputs minus total emissions.

The estimated emissions to Danish society are shown in Table 56.

Table 56. Estimated flows of PFASs to Danish society from lubricants in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	1.1	0	0	1.1	18	20
TFA related PFASs *	0	0	0	0	0	0
PFAAs and precursors	0.004	0	0	0.004	0.09	0.1
Total PFASs (rounded)	1	0	0	1	18	20

* Are included in section 2.2.15 on application of fluorinated gases.

2.2.13 Petroleum and other extraction sectors

Application

The PFAS restriction proposal group the use of PFASs in the petroleum and mining sectors, of which the petroleum sector is a major activity in Denmark. In Denmark, no actual mining takes place, and therefore certain uses (minor, such as flotation agents) described for the EEA are not relevant for Denmark. However, Denmark has significant extraction of sand, gravel and lime for construction purposes, and therefore PFASs may be relevant for this study in extraction equipment (moving parts).

The PFAS restriction proposal lists the uses relevant for Denmark as shown in Table 57.

Table 57. Sub-uses and application of PFASs in petroleum and mineral extraction sectors

Sub use	Application	Functions
Petroleum exploration and production	Drilling fluid/production chemicals	Fluorinated surfactants and anti-foaming agents
	Stimulation chemicals	Fluorinated surfactants
	Water and gas tracers	"Spike" markers to trace oil and gas reservoirs
	Fluoropolymer used in pipeline, valves, gaskets, O-rings, seals, cable and wiring insulation, flexible pipes	Sealings and insulation in harsh chemical environments
	Chemicals used in the storage or containment of oil and gas	Fluorinated surfactants creating a gas-evaporation barrier with water. Fluorocarbon lining of tanks (PTFE, etc.)
Mineral extraction	Fluoropolymer used in pipes, cables, hoses, conveyor belts, gaskets, bearings, membranes	Coatings, insulation, selective permeability

Firefighting foams are also used in these sectors; see section 2.2.14 for details.

Types of PFASs used

According to the PFAS restriction proposal, fluoropolymers are by far the main group of PFASs used in the petroleum and extraction industries.

Production in Denmark

There are indications that significant use of PFASs occurs in general manufacturing in Denmark, and it is known that coating of metal (and possibly other materials) with PFASs occurs in the country. The oil and gas extraction sector in Denmark is significant and a number of Danish companies are engaged in surface coating of equipment for the oil and gas sector. The following entries in the Danish Product Registry may relate to this group of applications (WEA, 2023):

- Surface treatment of metals, machine processing (<2 t PFAS/y)
- Manufacture of other finalised metal products (<6 t PFAS/y)
- Manufacture of machines and equipment, not specified elsewhere (<0.02 t PFAS/y)
- Specialised building and construction (<0.02 t PFAS/y)
- Other specialised building and construction (<0.03 t PFAS/y)

Quantities used

The PFAS restriction proposal estimates consumption of fluoropolymers of 3,500 - 7,000 t/y, and 1.0 and 3.4 - 8.5 t/y of water/gas tracers and production chemicals, respectively.

Oil and gas production-scaled consumption estimates for Denmark are given in Table 58. The relative Danish share of total EEA production was derived using the total production (in TJ) of crude oil and natural gas for Denmark, Norway and EU27, respectively (source for production data: IEA statistics accessed November 2023 at www.iea.org).

Table 58. Estimated consumption of PFASs in Denmark from the petroleum sector in 2021 (see text)

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and pre-cursors ***	**Total PFASs**
Water and gas tracers	0	0	0.02	0.02
Production chemicals	0	0	0.11	0.11
Fluoropolymers	102	0	0	102
Total PFASs (rounded)	102	0	0.13	102

* PFAS type used were assumed here based on their functions.

Trends in consumption and accumulation in society

According to a simplified trends analysis made in the PFAS restriction proposal, the consumption for this area has been relatively stable over the last decade.

Emission and distribution factors

The PFAS restriction proposal uses an alternative approach to estimating emissions from these sectors (compared to others). For fluoropolymers, i.e., the vast majority of the PFAS input, only residual monomers released from in the solid PFAS matrix are considered, whereas PFAS emissions from abrasion over the lifetime of end-uses are ignored. Using this methodology, the emissions are on the order of kilograms for the EEA; hence, corresponding emission numbers for Denmark are marginal. In this case, the PFAS restriction proposal disclosed all data needed for an element-to-element derivation of output distribution factors that were used in the calculation of corresponding output numbers for Denmark. However, while “total quantity entering waste” is presented (in Table B.45 of the restriction proposal), these do not appear to take into account the remaining PFASs in the end-uses brought to waste treatment. Therefore, the entire input of polymeric PFASs is assigned to waste treatment at end-of-life in this study. The resulting estimated emissions to the Danish environment are shown in Table 59; note the significant caveats described above.

Table 59. Estimated flows of PFASs to Danish society from the petroleum/extraction sector in 2021 (note text)

Group of PFASs	**Total outputs, t/y**					
	Air	**Surface water**	**Soil**	**Waste-water**	**Solid waste treatment**	**Total re-ported out-puts (rounded)**
Polymeric PFASs	0	0	0	0	102	102
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0.010	0.0007	0.011	0	0.009	0.03
Total PFASs (rounded)	0.010	0.0007	0.011	0	102	102

2.2.14 Firefighting foams

Application

Firefighting foams are addressed by a separate restriction proposal (ECHA, 2022) specific to this use. The specific restriction proposal was used as a key data source in this section of the current report. The specific restriction proposal presents the division of PFAS-containing firefighting foams consumption by sector shown in Figure 3. The designation “Ready for use products” are primarily reported to be fire extinguishers.

Firefighting foams are used for extinguishing fires that involve flammable liquids (ECHA, 2022). The main function of PFASs in firefighting foams is to act as a surfactant, that is to form a film over the surface of a burning liquid in order to prevent flammable gases from being released from it, as well as from reigniting.

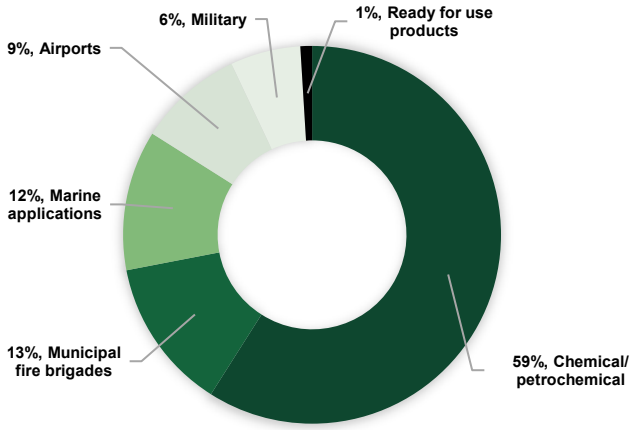


Figure 3. Split of PFAS-containing firefighting foams consumption by sector. Source: (reproduced from Wood, 2020, based on data provided by Eurofeu)

Types and quantities of PFASs used in the EU

Table 60 shows examples of PFASs used in firefighting foams along with their identified consumption within the EU from the firefighting foams restriction proposal. Note that as most of the tonnage is reported as unknown PFASs (due to confidentiality), the actual consumption of the identified substances may in fact be much more significant, assuming similarities in the substances/substance types used. Note also that these data provided by Eurofeu (Wood et al., 2020) are expected to cover about 60-70% of the EU market (Eurofeu), meaning that total EU consumption may be estimated at 480-560 t/y according to the firefighting foams restriction proposal.

Table 60. Types and amounts of PFASs identified in the EU in 2018 (Source: Eurofeu, presented by Wood et al., 2020). All substances are within the PFAAs and precursors group.

Specific PFAS	CAS number	Identified consumption, t/y
1-Propanaminium,N-(carboxymethyl)-N,N-dimethyl-3-[[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)sulfonyl]amino]-,inner salt	34455-29-3	21.1
1-Propanaminium, 3-amino-N-(carboxymethyl)-N,N-dimethyl-N-[[(gamma-omega-perfluoro-C6-C16-alkyl)thio]acetyl] derives., inner salts	80475-32-7	17.2
2-methyl-2 - [(1-oxo-3 -[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl) thio] propyl) amino]-1-propanesulfonic acid, sodium salt	62880-93-7	0.5
2-hydroxy-N,N,N-trimethyl-3-[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)thio]-1-Propanaminium, chloride (1:1)	88992-45-4	0.2
2-Propenamide, telomer with 4-[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)thio]-1-butanethiol)	Unknown	0.2
2-Propenoic acid, telomer with 2-propenamide and 4-[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)thio]-1-butanethiol, sodium salt	Unknown	0.3
2-Propenamide, telomer with 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-1-octanethiol	76830-12-1	0.9
unknown C-6 fluorinated substances	Unknown	17.1
Unknown 2	Unknown	138.6
Unknown 2	Unknown	138.6
Total identified by Eurofeu (2018)		**335**
Other substances identified as used by stakeholders:		
Carboxymethyldimethyl-3-[[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)sulphonyl]amino]propylammonium hydroxide	34455-29-3	NA
6:2 FTS		NA
Poly(1,1,2,2-tetrafluoro-1,2-ethanediyl),alphafluoro-omega-2-(3-((caboxylatomethyl)dimetylammonoi)propylaminosulfonyl)ethyl	NA	NA
Total EU, extrapolated via Eurofeu coverage		**480-560**

Production in Denmark

Fire-fighting foams containing PFASs are not produced in Denmark.

Quantities used in Denmark

The available data indicates that the use of PFAS-free foams in Denmark may be more widespread than indicated for the EU average.

At EU-level, in 2019, fluorine-free firefighting foams accounted for approximately 31% of the total market for fire-fighting foams. According to the restriction proposal for PFASs in fire-fighting foams (ECHA, 2022), the PFAS-foam market was 18,000 t/y (14,000-20,000 t/y) while the market for fluorine-free foams was estimated at 8,000 t/y (7,000-9,000). According to the proposal, several stakeholders, including manufacturers of firefighting foams, have indicated that the use of fluorine-free foams has been increasing, particularly in applications where PFAS-containing foams can easily be replaced.

A questionnaire survey on fire-fighting foams in Denmark has collected information on 69 fire-fighting foams used for training purposes in Denmark in 2022 (Henriksen et al., 2023). For

73% of the foams, the users responded that the foams did not contain PFASs, 10% of the foams did contain PFASs, and for 18% of the foams, the respondents did not know whether the foams contained PFASs. Of the 44 respondents, 11% answered that they use fire-fighting foams with PFASs, 55% said that they had changed to PFAS-free and 34% answered that they have never used foams with PFASs. The survey does not include a quantitative assessment of the foams that could have been used for a quantification of the volumes of fire-fighting foams used in Denmark. Furthermore, Wood (2020a) mentions that foams used for fire-fighting training in the Copenhagen Airport (CPH) do not contain PFASs. The total amount of PFASs in fire extinguishers reported to the Danish Product Registry is 0.1 t/y of PFAAs and others.

Whereas the PFAS-containing fire fighting foams at EU level accounted for approximately 69% of the EU market for fire fighting foams, available data indicate that the percentage of fire-fighting foams used in Denmark containing PFASs is closer to the range of 10-20%. To take this into account in the calculations, the *per capita* use of PFASs in fire-fighting foams in Denmark is assumed to be no more than 1/3 of the *per capita* consumption indicated in the restriction proposal.

A national ban prohibiting the import, sale and use of PFAS-containing fire-fighting foam concentrate at fire drill sites entered into force in Denmark on 1 January 2024 with prohibition deadlines for import and sale of 1st January 2024, and for use from 1 July 2024, respectively (BEK nr. 1360 af 27/11/2023).

Assuming a *per capita* consumption in Denmark in 2021 of 1/3 the EU consumption in 2018, the consumption of PFASs with firefighting foams in Denmark can be estimated as shown in Table 61. Assuming a predominance of substances similar to those identified in Table 60, all PFAS consumption for this use is categorized as “PFAAs and precursors”.

Table 61. Estimated consumption of PFASs in Denmark with firefighting foams in 2021

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Firefighting foams	0	0	2.3	2.3

Trends in consumption and accumulation in society

The firefighting foams restriction proposal assumes a steady state PFAS consumption with this use, noting that it may introduce uncertainties as there may be a trend away from PFASs in firefighting foam (meaning a gradual shift towards fluorine-free substances).

Emission and distribution factors

The firefighting foams restriction proposal estimates the annual emissions of PFASs shown in Table 62 by sector/type of use. The releases to the environment includes releases to sewage treatment plants, but the restriction proposal does not provide a split among the different compartments.

Table 62. Total estimated emissions to the environment of PFASs from firefighting foams by sector/use in EU27 (source: ECHA, 2022)

Sector/type of use	Annual emissions "best scenario", t/y *
Oil/(petro-)chemical industry (Seveso establishments)	200
Other industries	<10
Civilian aviation	40
Defence	20
Municipal fire services	50
Ready-to-use applications	<10
Marine applications	50
Training and testing	80
Total	~470

* Indicated as "rounded figures"

The firefighting foams restriction proposal worked with the assumption that all PFASs in the foams used for real incidents would be released to the environment during use, whereas for non-marine trainings, 97% was assumed captured and directed to wastewater treatment and the rest released directly to the environment. 97% captured seems high in the Danish context as the authors' own observations indicate that Danish training grounds often have semi-permeable surfaces, and actual releases from trainings directly to the environment may thus be higher. The knowledge of risks related to PFAS releases among relevant practitioners may have increased in the last few years; however, by 2022, non-PFAS firefighting foams were applied under most training circumstances (Henriksen et al., 2023).

For marine trainings, all PFASs are assumed released to the environment. The percentages assumed released to the environment by pathway were as follows:

- Non-marine uses: 50% to surface (fresh) water, 50% to soil
- Marine uses: 100% to marine water

The emissions to Danish society, estimated based on the assumption that the same distribution of outputs as for the EU apply, and combined with the emission factors mentioned, are shown in Table 63. Note that in this study, surface water is a combination of direct discharges to freshwater and marine waters.

Table 63. Estimated flows of PFASs to Danish society from firefighting foams in 2021

Group of PFASs	**Total outputs, t/y**					
	Air	**Soil**	**Surface water**	**Sewage**	**Waste treatment**	**Total outputs (rounded)**
Polymeric PFASs	0	0	0	0	0	0
TFA related PFASs	0	0	0	0	0	0
PFAAs and precursors	0	0.9	1.1	0.4	0	2.3
Total PFASs (rounded)	0	0.9	1.1	0.4	0	2.3

2.2.15 Applications of fluorinated gases

Application

The primary application of F-gases is as heat transfer media in cooling/warming (refrigerators, freezers, air conditioning, and heat pumps). However, as stated in the PFAS restriction proposal, PFAS gases are also applied as so-called “functional fluids”, typically solvents used for application of lubricants onto surfaces, cleaning of surfaces before lubrication, and similar, but also as fluid heat transporters (technical appliances immersed in fluids to disperse heat).

Types of PFASs used

PFAS-gases include a variety of short, low-weight, volatile fluorinated hydrocarbons (and related) substances, with at least one carbon atom fully fluorinated (as per the definition of PFAS). The specific substances included under this use category are those listed in Table 64 and Table 65 (for the latter, there is little quantitative information available).

Production in Denmark

Fluorinated gases are not produced in Denmark, but they are applied in production processes (as mentioned for several sectors above).

The Danish Products Registry has entries for use of the following PFAS gases in production in Denmark, together constituting the majority of the PFASs registered in the Product Registry (WEA, 2023):

- 2,3,3,3-tetrafluorprop-1-en (HFO-1234yf; <13 t PFAS/y)
- 1,1,1,2-tetrafluorethan (HFC-134a) (<29 t PFAS/y)

The sectors in the Product Registry in which these fluorinated gases may be used include, possibly among others (WEA, 2023):

- Maintenance and repair of motor vehicles (the only sector where a fluorinated gas is explicitly mentioned: 1,1,1,2-tetrafluorethan; part of 13 t PFAS/y of which some is PTFE and possibly also other PFAS)
- Manufacture of other machines for general purposes (<19 t PFAS/y; of which some may be a chemical other than fluorinated gases)

Quantities used and emitted

The consumption and emissions of the main F-gases are quantified in detail in the report “Danish consumption and emission of F-gases in 2021” (Poulsen, 2023), which includes both bulk net imports and net imports of products with F-gases incorporated. Some F-gases relevant for GWP estimation are not PFAS, and these were excluded in this study (SF6, HFC-152a, HFC-32, HFC-23). Emission estimates are based on current outputs, meaning that they take into account accumulation in society over the relevant lifetimes.

In addition, some PFAS-gases identified as relevant by the PFAS restriction proposal were not covered in the latest Danish F-gas report (Poulsen, 2023); these are listed in Table 65. As shown, trade statistics are not available for most of these, but two of them were covered as part of a group of 3 substance isomer groups by Statistics Denmark’s import/export statistics. However, until 2021, no import or export was registered (or publicly available). In 2022, after the reference year of the current report, a net import of the 3 substance isomer groups of 17.5 t/y was nonetheless registered. Import of other substances identified in the PFAS restriction proposal cannot be ruled out (as not all substances are covered by the Combined Nomenclature commodity codes), but data for their possible import are not available.

According to the PFAS restriction proposal, HFOs/HCFOs represented 24% of the total F-gas consumption in 2019. The exact fraction of these two PFAS groups among PFAS gases

(excluding some F-gases that are not PFAS) is not known, but 24% is used to estimate the assumed contribution from HFOs/HCFOs in this study. Therefore, the additional contributions from HFOs/HCFOs are calculated as the total consumption of (other) PFAS gases quantified in the Danish F-gas report (Poulsen, 2023) multiplied by 0.32 (0.24/0.76), and assuming a similar output distribution as for the total of other PFAS gases (the 0.76 is used to take into account the quantities multiplied with do not include the HFOs/HCFOs).

Table 64. Estimated consumption and flows of PFASs in Denmark from applications of fluorinated gases in 2021 (based on Poulsen, 2023 and ECHA, 2023).

Sub-use	Substances (PFASs)	Annual input (t/y)	Annual emissions to air (t/y)	Flow to waste (see text, t/y)
Refrigerants for commercial refrigerators and A/C systems	HCF-134a, HFC-404A, HFC-407C, HFC-410A, HFC-449A, HFC-452A, HFC-507	170.5	62.6	20
Refrigerants in “household” fridges/freezers *	HCF-134a, HFC-404A, PFC-14	0.8	0.9	0
Insulation foams in “household” fridges/freezers *	HFC-134	0	0	0
Refrigerants for mobile A/C systems	HCF-134a	55.1	55.1	0
Refrigerants for vans and lorries	HCF-134a, HFC-404A, HFC-410A, HFC-452a	4.7	3.2	0
Aerosol sprays	HCF-134a	0	0	0
MDI	HCF-134a, HCF-227ea	6.7	6.7	0
Heat pumps	HFC-407C, HFC-410A	126.9	23.0	15
Liquid cleaners	PFC	0	0	0
Fibre optics	PFC-14, PFC-318	0	0	0
Total (rounded)		**365**	**152**	**34**
Calculated contributions from HFOs/HCFOs	HFOs/HCFOs	115	48	11
Total incl. HFOs/HCFOs		480	200	45

* The products are not used in households, but typically in laboratories.

Table 65. F-gases identified as relevant PFAS-gases in the PFAS restriction proposal (ECHA, 2023), but not covered in Danish F-gas report (Poulsen, 2023)

Substance	Code	Net import to DK 2021
1-Chloro-1,2,2,2-tetrafluoroethane	HCFC-124	NA
3,3-Dichloro-1,1,1,2,2-pentafluoropropane	HCFC-225ca/cb	NA
1-Chloro-2,3,3,3-tetrafluoropropene	HFO-1224yd(Z) *	NA
1-Chloro-3,3,3-trifluoro-1-propene	HFO-1233zd(E) **	NA
2,3,3,3-Tetrafluoropropene	HFO-1234yf	NA
Trans-1,3,3,3-tetrafluoroprop-1-ene	HFO-1234ze(E) ***	NA
1,3,3,3-Tetrafluoropropene	HFO-1234ze(E) ***	NA
Trans-1,1,1,4,4,4-hexafluorobut-2-ene	HFO-1336mzz(E)	0 (1)
Cis-1,1,1,4,4,4-hexafluoro-2-butene	HFO-1336mzz(Z)	0 (1)
(Z)-1-Chloro-2,3,3,3-tetrafluoropropene	HCFO-1224yd *	NA
Trans-1-chloro-3,3,3-trifluoropropene	HCFO-1233zd(E) **	NA
2-Bromo-3,3,3-trifluoroprop-1-ene	BTP, 2-BTP, Halotron BrX	NA

Substance	Code	Net import to DK 2021
Methoxytridecafluoro-heptene isomers	MPHE, SionTM	NA
Dodecafluoro-2-methyl-3-pentanone	FK-5-1-12 (fluoroketone)	NA
1,1,2,2-Tetrafluoro-1-(2,2,2-trifluoroethoxy) ethane	HFE-347pc-f2	NA
Methyl perfluoropropyl ether	HFE-7000	NA
Methyl nonafluorobutyl ether + Methyl nonafluoroisobutyl ether	HFE-449mccc/HFE-449s1 (HFE-7100)	NA
1-Ethoxy-nonafluorobutane	HFE-569mccc/HFE-569sf2 (HFE-7200)	NA
3-Methoxyperfluoro(2-methylpentane)	HFE-7300	NA
3-Ethoxyperfluoro(2-methylhexane)	HFE-7500	NA
Hexafluoroisopropanol	HFIP	NA
2,3,3,3-tetrafluoro-2-(trifluoromethyl)- propanenitrile	C4-FN	NA
1,1,1,3,4,4,4-heptafluoro-3-(trifluoromethyl)-2-butanone	C5-FK	NA
(E)-1,1,1,2,3,4,5,5,5-nonafluoro-4-(trifluoromethyl)- 2-pentene	FA-188	NA
Perfluorohexane (n- and iso-)	FC-72/PF-5060	NA
Perfluorotripropylamine (perfluamine)	FC-3283	NA
Perfluorotributylamine	FC-40	NA
Perfluoro-N-propylmorpholine (mixture of isomers)	FC-770	NA
Perfluoro-2-methylpentane	Flutec RC1	NA
1,1,2,3,3,3-Hexafluoropropene, oxidized, polymerized (Perfluoropolyether, PFPE)	Galden HT-55/HT-70	NA

Note: HFO-1336mzz is a part of commodity code 2903.5100, named “29035100 2,3,3,3-Tetrafluorpropen HFO-1234yf, 1,3,3,3-tetrafluorpropen HFO-1234ze and (Z)-1,1,1,4,4,4-hexafluor-2-buten HFO-1336mzz”, for which there is no trade reported until 2022, where the net import of the group was 17.5 t/y. HFO-1234yf is not among the substances identified as relevant in the PFAS restriction proposal (Table A.96).

Trends in consumption and accumulation in society

Trends are incorporated into the emission estimates from Poulsen (2023) shown above.

Emission and distribution factors

All emissions are assumed to be to air. The numbers estimated by Poulsen (2023) do not enable a clear quantification of F-gases going to waste treatment, as the difference between current inputs and current emissions are not described in detail. However, Poulsen (2023) indicates that 11.5% of the F-gases in refrigerants and A/C systems are lost during decommissioning, assumed to waste treatment in this study. For lack of more precise data, 11.5% of the current input is considered lost to waste treatment from commercial cooling and heat pumps.

In summary, the quantifiable outputs of F-gases in Denmark are shown in Table 66.

Table 66. Estimated flows of PFASs from Danish society from applications of PFAS gases in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0	0	0	0	0	0
TFA related PFASs	200	0	0	0	45	245
PFAAs and precursors	0	0	0	0	0	0
Total PFASs (rounded)	200	0	0	0	45	245

2.2.16 Pesticides

Application

Certain PFASs are applied as active substances in plant protection products and biocidal products (collectively referred to as pesticides).

Types of PFASs used

The types of PFAS active substances in products authorised for use in Denmark in pesticides are listed in Table 67 below.

The active substances all have one or two -CF_3 moieties apart from one active substance (fludioxonil) which has a -CF_2- moiety. None of the substances have two or more fluorinated carbon atoms in a chain.

The substances with a -CF_3 moiety may potentially be degraded to TFA. It is uncertain to what extent the active substances may be degraded to TFA. For some pesticidal agents such as flurtamone and flufenacet (not used in Denmark), degradation studies were submitted as part of the approval process, showing the formation of TFA (Umweltbundesamt, 2021). However, for many of the plant protection products, the potential formation of TFA has not been evaluated as part of the approval process; therefore, it is uncertain as to what extent TFA would be formed by the degradation of the active substances.

Some PFASs may be used as co-formulants in pesticides. Contrary to the active substances, the co-formulants are regulated under REACH and consequently included in the PFASs addressed by the PFAS restriction proposal. No information on PFAS co-formulants in plant protection products or biocidal products approved for the EU market have been identified.

Production in Denmark

Some PFAS active substances for pesticides are produced in Denmark by fewer than four companies. For confidentiality reasons, data on production volumes cannot be disclosed.

The following entry in the Danish Products Registry may relate to this group of applications (WEA, 2023): Production of chemicals (0.01 t PFAS/y).

Quantities used

Quantities of PFAS active substances in pesticides sold in Denmark in 2019-2021 are shown in Table 67. The data were extracted from the Danish pesticides statistics (In Danish “Bekæmpelsesmiddelstatistikken”, Danish EPA, 2023b). The search for PFAS active substances is based on the non-exhaustive lists of PFAS active substances in plant protection products and biocidal products in the PFAS restriction proposal (Appendix A.3.17 in ECHA, 2023) supplemented with five PFAS active substances identified by the Danish EPA (MOF, 2023):

Fludioxonil (CAS No 131341-86-1), Indoxacarb (CAS No 173584-44-6), Fluazifop-P-butyl (CAS No 79241-46-6), Flur-primidol (CAS No 56425-91-3) and tau-Fluvalinate (CAS No 102851-06-9).

In total, there are currently 14 PFAS active substances in products authorised for use in Denmark. The table below includes only substances with registered sales in the years of concern. It should be noted that additional biocidal products of potential relevance are still undergoing the approval process in the EU and are therefore not included in Table 67.

The total quantity of PFAS active substances in plant protection products sold in Denmark in 2021 was 172.4 t/y. The total quantity estimated for the EU was 5,479 t/y according to the PFAS restriction proposal (ECHA, 2023) extrapolated to the EU from data from the Netherlands. On a *per capita* basis, the consumption in Denmark was approximately twice the consumption in the Netherlands.

Table 67. Quantities of PFAS active substances in plant protection products and biocidal products sold in Denmark in 2019-2021 (Danish EPA, 2023b)

Active substance name	Chemical name	CAS No	Active substance, kg		
Plant protection products			**2019**	**2020**	**2021**
Diflufenican	N-(2,4-difluorophenyl)-2-[3-(trifluoromethyl)phenoxy]-3-pyridinecarboxamide	83164-33-4	38,223	48,242	61,262
Flonicamid	N-(cyanomethyl)-4-(trifluoromethyl)pyridine-3-carboxamide	158062-67-0	1,107	1,236	790
Fluazinam	3-chloro-N-[3-chloro-2,6-dinitro-4-(trifluoromethyl)phenyl]-5-(trifluoromethyl)pyridin-2-amine	79622-59-6	7,602	10,331	8,580
Fludioxonil	4-(2,2-difluoro-1,3-benzodioxol-4-yl)-1H-pyrrole-3-carbonitrile	131341-86-1	3,020	4,415	2,115
Fluopyram	N-(]2-[3-chloro-5-(trifluoromethyl)pyridin-2-yl]ethyl)[)-2-(trifluoromethyl)benzamide	658066-35-4	33,789	46,542	46,945
Indoxacarb	methyl (4aS)-7-chloro-2-[methoxycarbonyl-[4-(trifluoromethoxy)phenyl]carbamoyl]-3,5-dihydroindeno[1,2-e][1,3,4]oxadiazine-4a-carboxylate	173584-44-6	460	519	643
lambda-Cyhalothrin	[(R)-cyano-(3-phenoxyphenyl)methyl] (1S,3S)-3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropane-1-carboxylate	91465-08-6	3,324	2,771	3,702
Mefentrifluconazole	2-(4-(4-Chlorophenoxy)-2-(trifluoromethyl)phenyl)-1-(1H-1,2,4-triazol-1-yl)propan-2-ol	1417782-03-6	0	0	29,699
Pyroxsulam	N-(5,7-dimethoxy[1,2,4]triazolo[1,5-a]pyrimidin-2-yl)-2-methoxy-4-(trifluoromethyl) pyridine-3-sulfonamide	422556-08-9	1,909	2,169	2,837
Tau-fluvinate	[cyano-(3-phenoxyphenyl)methyl] (2R)-2-[2-chloro-4-(trifluoromethyl)anilino]-3-methylbutanoate	102851-06-9	12,262	7,906	11,453
Tefluthrin	2,3,5,6-tetrafluoro-4-methylbenzyl (1RS,3RS)-3-[(Z)-2-chloro-	79538-32-2	3,520	1,440	3,880

Active substance name	Chemical name	CAS No	Active substance, kg		
Plant protection products			**2019**	**2020**	**2021**
	3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropanecarboxylate				
Triflusulfuron-methyl	"methyl 2-(()([4-(dimethylamino)-6-(2,2,2-trifluoroethoxy)-1,3,5-triazin-2-yl]carbamoyl)[)sulfamoyl)-3-	126535-15-7	225	205	543
Total active substance, plant protection products			**105,441**	**125,774**	**172,448**
Biocidal products (see body text)					
lambda-Cyhalothrin	[(R)-cyano-(3-phenoxyphenyl)methyl] (1S,3S)-3-[(Z)-2-chloro-3,3,3-trifluoroprop-1-enyl]-2,2-dimethylcyclopropane-1-carboxylate	91465-08-6	2.4	2.8	128.2
Indoxacarb	methyl (4aS)-7-chloro-2-[methoxycarbonyl-[4-(trifluoromethoxy)phenyl]carbamoyl]-3,5-dihydroindeno[1,2-e][1,3,4]oxadiazine-4a-carboxylate	173584-44-6	4.1	2.9	1.9
Total active substance, biocidal products			**6.5**	**5.7**	**131.1**
Grand total			**105,447**	**125,780**	**172,579**

A summary of the registered consumption of PFAS active substances in plant protection products and biocidal products is given in Table 68.

Table 68. Summary of registered consumption of PFAS in Denmark with pesticides in 2021

	Consumption with end products, t/y			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
Plant protection products	0	172.4	0	172.4
Biocidal products *	0	0.13	0	0.13
Total (rounded)*	0	173	0	173

* Additionally, there may be a potentially significant, unquantified input from biocidal products that are not yet approved.

Trends in consumption and accumulation in society

As shown in Table 67, there appears to be an increasing trend in the sales of plant protection products with PFAS active substances in Denmark in recent years.

Emission and distribution factors

As most plant protection products are intended to be applied on land, and as the losses of active substances in packaging materials and obsolete products are assumed to be negligible under Danish conditions, 99.95% of the consumption of PFAS with plant protection products is considered released to soil in this study. Based on the data on deposition presented in section 5.2, an emission factor for air is estimated at 0.05%. Biocidal products are a significantly more diverse group in terms of application patterns than plant protection products, as circumstances during use will be varied. Biocidal products based on lambda-cyhalothrin (a main biocidal product) are used as insecticide both indoors and outdoors. For simplicity and lacking more precise data, this study assumes that under Danish conditions, 50% of the biocidal product amount used would be released to wastewater and 50% to soil.

The estimated releases of PFAS with pesticides from Danish society are summarised in Table 69.

Table 69. Estimated flows of PFASs in pesticides from Danish society in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0.00	0.0	0	0.0	0	0.0
TFA and related PFASs	0.09	172	0	0.06	0	173
PFAAs and precursors	0.00	0.0	0	0.00	0	0
Total PFASs (rounded)	0.09	172	0	0.06	0	173

2.2.17 Pharmaceuticals

This section includes:

- PFAS Active Pharmaceutical Ingredients (API) in human medicinal products
- PFAS Active Pharmaceutical Ingredients (API) in veterinary medicinal products

Application

According to the PFAS restriction proposal, active substances that fulfil the PFAS definition are commonly characterized by the presence of one or more CF_3-group(s) in their molecular structure. Introducing this group in the molecular structure of biologically active substances could enhance specific properties, such as stability, lipophilicity, etc.

Types of PFASs used

A wide array of organic substances is applied in pharmaceuticals. The PFAS restriction proposal does not give details on specific PFASs used.

Production in Denmark

Production of pharmaceuticals forms a significant sector in Denmark. No information was, however, encountered on whether PFASs are used specifically in production in this sector in the country. However, the following entry in the Danish Product Registry may relate to this group of applications (WEA, 2023):

- Production of chemicals (0.01 t PFAS/y)

Quantities used

According to the PFAS restriction proposal, the use of PFAS Active Pharmaceutical Ingredients (API) in human medicines in the EU is >500 t/y.

For PFAS Active Pharmaceutical Ingredients (API) in veterinary medicines, no input information is available in the restriction proposal. According to EFPIA (2023) "*in the veterinary field, a number of fluorinated compounds for the treatment of life-threatening infections and (potentially zoonotic) parasite infestations have been identified with 16 of those qualifying as PFAS under the OECD definition and, as such, falling under the proposed PFAS restriction.*" As no data are available, veterinary pharmaceuticals are not included in the quantitative assessment in this study.

In Denmark, the use of pharmaceuticals for veterinary uses is reported in the VetStat statistics [21]. The publicly available statistics do not include quantities used of the individual pharmaceuticals and cannot be used for estimating the number of veterinary pharmaceuticals falling under the PFAS definition used in Denmark.

Using *per capita* scaling, the approximate level of consumption in Denmark is shown in Table 70.

Table 70. Estimated consumption of PFASs in Denmark with human and veterinary pharmaceuticals in 2021

	Consumption with end products, t/y (midpoint estimate)			
Sub use	**Polymeric PFASs**	**TFA related PFASs**	**PFAAs and precursors**	**Total PFASs**
PFAS Active Pharmaceutical Ingredients (API) in human medicinal products *	0	6.5	0	6.5
PFAS Active Pharmaceutical Ingredients (API) in veterinary medicinal products	0	n.d.	0	n.d.
Total quantified	0	6.5	0	6.5

* Excluding propellants in, for example, MDIs, as they are dealt with elsewhere in this report and they are not active ingredients. n.d.: no data available.

Trends in consumption and accumulation in society

No information was available as regards trends in PFAS use in these applications; the lifetime is assumed to generally be less than 1 year.

Emission and distribution factors

For human pharmaceuticals, it is assumed in this study that the majority is released to sewage via human excretion; it is therefore assumed that 95% of the current output is released to wastewater, while the remaining 5% is disposed of (as obsolete pharmaceuticals, etc.) to waste treatment. Note that the PFASs excreted are not necessarily identical to the PFASs ingested, as degradation in the human digestion system takes place. Due to the complexity involved, this factor has not been possible to account for in detail in this study.

The estimated emissions to Danish society are summarised in Table 71.

Fate of the PFAS active substance. The fate of the pharmaceuticals and the formation of metabolites falling under the PFAS definition may vary by pharmaceuticals. An example for the pharmaceutical Flecainide is described here. According to EFPIA (2022), the pharmaceutical Flecainide has the highest API (active pharmaceutical ingredient) volume in the Report Summary provided with PFAS restriction proposal Stakeholder Consultation. The molecule is not persistent in the human body and the half-life for Flecainide was 12 to 27 hours in patients. Approximately 86% of a single oral dose is excreted with urine, with 42% as unchanged Flecainide and 14% as meta-O-dealkylated Flecainide, a similar amount of the meta-O-dealkylated lactam of flecainide, approximately 3% as an unidentified acid metabolite, and <1% as 2 other unknown metabolites. 5% is eliminated in the faeces (Drugbank online). In total about 91% is excreted with urine and faeces. Flecainide has a molecular weight of 414 g/mol and includes two -CF_3 moieties which ultimately may be degraded to TFA. The molecular weight of TFA is 114 g/mol and with two -CF_3 moieties, the weight of the TFA degradation product would correspond to 55% of the weight of Flecainide if all of the -CF_3 moieties are

[21] https://foedevarestyrelsen.dk/dyr/dyresundhed/laegemidler-til-dyr/vetstat/vetstat-for-borgere

converted to TFA. Most of the PFAS pharmaceuticals have one -CF_3 only, and the weight of the potentially formed TFA would be less than the 55% calculated for Flecainide.

Estimated flows. The estimated flows of PFASs from Danish society from the application of pharmaceuticals in 2021 is shown in the table below.

Table 71. Estimated flows of PFASs from Danish society from the application of pharmaceuticals in 2021

Group of PFASs	Total outputs, t/y					
	Air	Soil	Surface water	Sewage	Waste treatment	Total outputs (rounded)
Polymeric PFASs	0	0	0	0	0	0
TFA related PFASs	0	0	n.d.	6.2	0.3	6.5
PFAAs and precursors	0	0	0	0	0	0
Total PFASs (rounded)	0	0	0	6.2	0.3	6.5

n.d.: No data. The potential release af PFASs to soil from the use of veterinary pharmaceuticals is not quantified as no data on the use of veterinary pharmaceuticals with PFAS active ingredients have been available.

2.3 Summary of uses in Denmark

A summary of the input to society of PFASs by group and application areas in Denmark in 2021 is shown in Table 72.

Table 72. Estimated intentional input to society of PFASs by group and application areas in Denmark in 2021 with indication of uncertainty ranking

	Input to the society, t/y (midpoint estimate)			Uncertainty ranking
Applications area	**PFAAs and pre-cursors**	**TFA related substances**	**Polymeric PFAS**	
Apparel	100	0	400	Medium
Textiles, upholstery, leather, and carpets	72	0	520	Medium
Food contact materials	50	0	230	High
Metals plating / metal products	0.4	0	10	High
Consumer mixtures	0.4	0	0	High
Cosmetics	0.4	0	0	High
Ski wax	0.02	0	0	High
Medical devices	30	0	100	High
Transport sector	7	0	140	High
Electronics & manufacture of semi-conductors	15	0	40	High
Energy sector	4	0	40	High
Construction materials/products	22	0	90	High
Lubrification	0	0	20	High
Oil-gas & other extraction	0.13	0	102	Medium
Firefighting foams	2.3	0	0	High
PFAS gas uses	0	480	0	Low
Pesticides	0	173	0	Low & high
Pharmaceuticals	0	6.5	0	Medium
Sum	300	660	1,690	

Uncertainty ranking: Low : The actual value is most likely within a range of ±25% ; Medium: The actual value is most likely more than 1/3 and less than three times the best estimate. High: The actual value may be less than 1/3 or more than 3 times the best estimate.

3. Turnover as unintentional impurity

3.1 Formation by natural processes and as byproduct

In general, polymeric PFAS, PFAAs and precursors are not formed by natural processes or as by-products.

However, some PFASs may be formed as a by-product of other manufacturing processes. A significant emission source of fluorinated gases (specifically tetrafluoromethane and hexafluoroethane) is the aluminium and rare earth metal smelting industry (Kim et al., 2021 as cited by ECHA et al., 2023). Aluminium production and rare earth metal smelting do not take place in Denmark.

In addition TFA may be formed by natural processes under extreme conditions - like undersea hydrothermal vents (Solomon et al., 2016; UNEP, 2015 as cited by ECHA, 2023). However, according to ECHA (2023), discussion has been taking place on the relevance of natural sources of TFA in the environment, especially when it comes to non-marine environments. TFA has been indicated to have natural sources in oceans (underwater vents) but evidence for the existence of natural TFA is considered insufficient to substantiate this claim. Oceans are considered the final environmental sink of the substance. TFA in the atmosphere, precipitate, freshwater bodies and conifers needles most likely stems from anthropogenic sources (ECHA, 2023).

Natural production of TFA and PFAAs and precursors (if any), as well as byproduct formation of fluorinated gases by aluminium production and the rare earth metal smelting industry, is not further considered in this study.

3.2 Presence as impurity in recycled or contaminated materials

PFASs present as unintentional impurities in PFAS-containing products. According to the PFAS restriction proposal, based on the complex interplay of PFASs, it is difficult to state whether individual substances are used intentionally in some cases or if they are the product of degradation or an impurity. The estimates for consumption of PFASs for the various application areas are considered to include all PFASs in the products, irrespective of whether the substances are present as residual impurities in the products.

PFAS impurities in packaging. PFASs may be present in packaging as unintentional contaminants from recycled paper and cardboard. The PFAS restriction proposal specifically indicates that unintentional contaminants are included in the estimated quantities used for this application area; consequently, they are included in section 2.2.2 of this study.

PFAS impurities in other recycled products. It cannot be excluded that PFASs may be present as contaminants in other recycled products, but no specific data have been available to substantiate this. As fluoropolymers cannot be mixed with thermoplastics, contamination of recycled plastics with fluoropolymers is not considered to be an issue. A study for the Danish EPA of recycled plastics used for packaging of cosmetic products did not find PFASs or total fluorine content above the limit of quantification (Kastbjerg et al., 2021).

PFAS impurities in textile fibres recovered from discarded textiles, e.g. for industrial cloths, may contain PFASs if the recovered textiles include outdoor apparel. No data on PFASs in articles of recovered textile fibres have been identified.

3.2.1 Manure

No data on PFASs in manure are available from Denmark.

In a recent study from France, Munoz et al. (2022) measured PFASs in agriculture-derived wastes such as pig slurry, poultry manure, and dairy cattle manure. The median ∑160 PFASs concentration was 0.62 µg/kg d.w. and the average was 0.81 µg/kg d.w., which was considerably lower than the concentration in sewage sludge and other urban derived wastes. The main PFAS classes determined in the manure were FASAA (main), PFSA and PFCA. In comparison, the mean concentration of $PFAS_{22}$ in sewage sludge in Denmark is estimated at 15.3 µg/kg d.w. The total annual production of livestock manure in Denmark is approx. 43 million tonnes wet weight, of which 96% comes from cattle and pigs (Hinge et al., 2020). The report does not indicate the tonnage in dry weight (d.w.) but it can be converted to approximately 3.6 million tonnes d.w. using the conversion factor used by Birkmose et al. (2013). If the mean concentration from the French study is applied, the total PFAAs' and precursors' content of the produced manure can be estimated at 2.4 kg/y. Some of this will be processed in biogas reactors before being applied onto agricultural land, but it is assumed in this study that the total quantity ultimately will be applied to soil. Other feedstock for biogas production (apart from sewage sludge, addressed separately in section 4.2.3) may also contain low levels of PFASs, but no data are available. Therefore, this source has not been further investigated.

According to Umweltbundesamt (2021), liquid manure can contain TFA or its potential precursors, e.g. via the use of veterinary pharmaceuticals and biocidal products. In order to analyse the potential sources of TFA to soil, the worst case emission scenario of TFA in manure was estimated on the basis of individual measurements of TFA in liquid manure. However, it is noted by Umweltbundesamt (2021) that the samples may not necessarily be representative and should be verified by further measurements. The potential TFA releases with manure (mainly in the form of potential TFA precursors) are estimated at 2.8 kg/ha, as compared to sludge, which is estimated at 36 kg/ha. Compared to the TFA potential of applied plant protection products (which is calculated as tonnage of the PFAS active substances in plant protection products and not tonnage of potential generated TFA in the current study), the potential of the liquid manure is very small (Umweltbundesamt, 2021). As indicated in section 2.2.17, no data have been available on quantities of PFAS veterinary pharmaceuticals used in the EU or Denmark. Considering the high uncertainties, the possible release of TFA related substances to soil by application of manure has not been estimated.

4. Turnover with solid waste and wastewater

The PFAS restriction proposal notes that estimates of emissions from waste treatment are highly uncertain due to limited data. Estimates based on the available studies suggest a total EEA waste stage emission of 1 - 6 t/y (extrapolated to the Danish situation, this corresponds to approximately 10-60 kg/y). Additional calculations based on knowledge of the use of PFASs in the EEA, in combination with ECHA ERCs (Environmental Release Categories), lead to EEA waste stage emissions ranging between approximately 3,700 to 7,300 t/y, i.e., nearly 1000 times higher. The discrepancy between the estimates may partly be explained by the fact that actual monitoring data only represent a part of the total PFASs in the emissions. However, it may also reflect that the ERCs, which are default emission factors and not specific for PFASs, may significantly overestimate the actual emissions.

The following section presents available data from Denmark on PFASs in the various flows, supplemented with data from other countries, in order to convert concentrations of target PFASs to total PFAS concentrations. The same discrepancy between modelled data and actual measurements, as mentioned above, is prominent for some flows.

4.1 Presence and fate of PFASs in solid waste management

4.1.1 Disposal methods and sources of PFASs in solid waste

The starting point for carrying out calculations of PFASs in the different waste streams are the estimates of PFASs disposed of, as calculated in section 2.2 for the application areas. For each of the application areas, the distribution across disposal methods was estimated on the basis of knowledge on main disposal pathways for the given application area. Different distributions are derived for polymeric PFASs and PFAAs and precursors.

Disposal of fluoropolymers at EU level. The PFAS restriction proposal generally has very limited information on disposal method by application area. For fluoropolymers, which account for the majority of the polymeric PFASs, some data on the disposal method at EU level are available (Conversio, 2022). The data are used in this study as indicators of the fate of fluoropolymers by waste treatment in Denmark, as this indicates the share of the fluoropolymers that follow the metal scrap. The data on distribution by disposal pathways are summarised in Table 73 to form the background for estimation of the most likely distribution in Denmark for these materials.

At EU level, metal recycling accounts for 12% of the polymeric PFASs disposed of. It is assumed that for Denmark, this part is included in metal scrap exported for recovery of the metals abroad (Table 73). At EU level, 3.4% of the fluoropolymers in waste is recycled (Table 73). This waste is nearly all production waste and hardly any recycling of fluoropolymers from post-consumer waste takes place. No information on recycling of fluoropolymers in Denmark has been identified and likely, no recycling takes place (apart from some internal recycling in companies).

As concerns the share between energy recovery (incineration) and landfill, it is assumed in this study that all waste is in the category “suitable for incineration” [Danish: “forbrændingsegnet”]. In Denmark, for most application areas, close to 100% of the waste “suitable for incineration” (which is not recycled) is incinerated with energy recovery. The share between energy recovery and landfill differs significantly from the EU average.

Table 73. Treatment of fluoropolymer waste by application area in the EU in 2020 (Conversio, 2022)

Application area	Collected fluoropolymer waste, 1000 t	Energy recovery	Landfill	Metal recycling	Fluoropolymer, recycling
Automotive	3.5	71.4	22.9	5.7	0
Aerospace	0.3	80.0	13.3	3.3	3.3
Electronics & semiconductors	2.7	79.6	9.3	5.6	5.6
Chemicals (CPI)	9.4	75.5	11.2	9.6	3.7
Medical & pharma	2.3	87.0	6.5	2.2	4.3
Other	5.3	54.7	15.1	26.4	3.8
Total	23.5	71.9	13.0	12.0	3.4

Distribution of waste by treatment types and by application area

Apparel. A fraction of the apparel disposed of in Denmark is recycled within the country, regarded an exceedance of the lifespan of the apparel but not an output pathway in this context, as the input to the society is estimated on the basis of the input of new apparel. In 2018, 36,000 t/y were collected. Of this, 11,000 t were recycled in Denmark, 2,230 t/y incinerated, and 22,000 t/y exported (Watson and Trzepacz, 2017). In addition, 40,000 t/y was disposed of to municipal solid waste, which was 100% incinerated. The distribution shown in Table 74 and 75 concern the fraction not recycled in Denmark. It is roughly assumed that apparel with PFASs follow the general distribution pattern.

Textiles, upholstery, leather, and carpets. Some products may be sold for reuse, which is considered to result in a longer life of the products but not as an ultimate disposal pathway in this study. The ultimate disposal partway for these products in Denmark is estimated to be 100% to incineration.

Food contact materials and packaging. For the polymeric PFASs, the main ultimate pathway is expected to be scrap exported for recovery abroad. Some car wrappings may be disposed of for incineration because of changing of the wrapping. This could account for some percentage of the total use of polymeric PFASs. Some industrial cookware is recoated; according to the restriction dossier, the quantities of polymers disposed of from recoating account for no more than 1% of the total. This part is expected to be disposed of to incineration. In total, 10% of the polymeric PFASs from the group is assumed to be disposed of for incineration.

The non-polymeric PFASs are assumed mainly to be disposed of with municipal solid waste for incineration or recycling of paper/cardboard/plastics. As the materials are contaminated with food to a large extent, the percentage recycled is expected to be significantly lower than the general recycling percentage of paper/cardboard/plastics in Denmark. It is consequently assumed that 80% is disposed of for incineration. The remaining is assumed to follow the general pattern for collected paper and cardboard in Denmark, of which 64% was exported in 2021 (Danish EPA, 2023e).

Metals plating/metal products. The PFASs are assumed to follow the metal scrap for recycling abroad. According to the restriction proposal, PFASs used as auxiliaries in metal plating processes (mist suppressors, etc.) are regularly disposed of to hazardous waste treatment along with metal plating sludges.

Consumer mixtures and cosmetics. The PFAS restriction proposal assumes that no PFASs are disposed of to solid waste.

Ski wax. A very small amount of PFASs is disposed of to solid waste; for Denmark it is assumed to be 100% disposed of for incineration in this study.

Medical devices. The PFAAs and precursors are assumed to be 100% disposed of to incineration. For the polymeric PFASs, a 80:20 split between incineration and scrap for export is assumed.

Transport sector. The PFAS refrigerants used are assumed to be collected during maintenance and treated along with other PFAS gases. Hydraulics are assumed to be collected and incinerated as hazardous waste. Other PFASs are assumed to be exported with scrap. Note that some refrigerants are directly reused; these quantities are included in neither consumption nor disposal.

Electronics (& manufacture of semi-conductors). Electronics are assumed to be collected as electronics waste (WEEE) and exported for recycling.

Energy sector. Wind turbine towers and batteries with PFASs are assumed to be collected separately and directed to materials treatment/regeneration. Other metal parts are assumed to be exported for scrap recycling. Of the fraction not collected, it is assumed that some is landfilled, e.g., with wind turbine blades, and that some is incinerated.

Construction materials/products. The PFAS restriction proposal lists a large number of applications of polymeric and non-polymeric PFASs used in construction materials/products but does not provide a detailed split of the quantities used. Depending on the application, the materials follow many different flows. For a number of applications where tiles, masonry and concrete are surface treated with, e.g., side-chain fluorinated polymers, the PFASs may follow the mineral materials: applications listed as architectural coatings and paints, surface protection, sealings and adhesives. Coatings of metal parts with PFASs are assumed to be exported, as scrap and coatings on combustible material are assumed to be incinerated. Wire and cables are assumed to be exported. Without information on the detailed split regarding consumption, the distribution pattern is very uncertain.

Lubrication. Polymeric PFASs used for lubrication are assumed to be exported with metals scrap. Unused grease/oil lubricants and containers are assumed to be collected and disposed of to hazardous waste incineration.

Petroleum & other extraction. Metal parts with PFASs are assumed to be exported as scrap.

Application of PFAS gases. The PFAS gases ultimately disposed of as waste are assumed to be 100% destroyed by incineration.

Table 74. Estimated disposal method distribution for PFAS-containing solid waste by application area for **PFAAs and precursors**. The table includes only those application areas for which some of the used PFAS-containing products are disposed of with solid waste. For each application area, the waste is divided into one or two waste categories and for each of these, the quantities are distributed by disposal method.

Application area	Process/ waste category 1	Fraction of group, %	Incinera-tion in DK	Land-filling in DK	Recy-cling/re-covery in DK	Recy-cling/recov-ery abroad *	Process/ waste category 2	Fraction of group, %	Incinera-tion in DK	Landfilling in DK	Recy-cling/re-covery in DK	Recy-cling/re-covery abroad *
Apparel	Municipal solid waste	61%	90%			10%	Apparel collection	39%	9%			91%
Textiles, upholstery, leather, and carpets	Municipal solid waste	100%	100%									
Food contact materials and packaging	Municipal solid waste	80%	100%				Paper/cardboard re-cycling	20%			36%	64%
Metals plating/metal products	Metal scrap	50%				100%	Hazardous waste	50%	50%			
Medical devices	Medical waste	100%	100%									
Transport sector	Shredder waste	90%	70%	30%			Metal scrap	10%				100%
Electronics & manufacture of semi-conductors	Electronics waste	100%	20%			80%		0%				
Energy sector	Industrial waste	80%	90%			10%	Batteries and elec-tronics	20%				100%
Construction materials/prod-ucts	Building waste	100%	80%	20%								
Lubrification	Hazardous waste	100%	100%									
Petroleum & other extraction	Industrial waste	80%	90%			10%	Metal scrap	20%				100%
PFAS gas uses	Hazardous waste	100%	100%									

* Include processes where the PFASs follow other materials (typically metals) for recovery of these materials

Table 75. Estimated disposal method distribution for PFAS-containing solid waste by application area for **Polymeric PFASs**. The table includes only those application areas for which some of the used PFAS-containing products are disposed of with solid waste. For each application area, the waste is divided into one or two waste categories and for each of these, the quantities are distributed by disposal method.

Application area	Process/ waste category 1	Fraction of group, %	Incinera-tion in DK	Land-filling in DK	Recy-cling/re-covery in DK	Recy-cling/recov-ery abroad *	Process/ waste category 2	Fraction of group, %	Incinera-tion in DK	Landfilling in DK	Recy-cling/re-covery in DK	Recy-cling/re-covery abroad *
Apparel	Municipal solid waste	61%	90%			10%	Apparel collection	39%	9%			91%
Textiles, upholstery, leather, and carpets	Municipal solid waste	100%	100%					0%				
Food contact materials and packaging	Metal scrap	40%				100%	Incineration	60%	100%			
Metals plating/metal products	Metal scrap	100%				100%		0%				
Medical devices	Medical waste	80%	100%				Metal scrap	20%				100%
Transport sector	Shredder wastes	90%	70%	30%			Metal scrap	10%				100%
Electronics & manufacture of semi-conductors	Electronics waste	100%	20%			80%		0%				
Energy sector	Industrial waste	90%	50%	30%		20%	Batteries and elec-tronics	10%				100%
Construction materials/prod-ucts	Building waste	80%	80%			20%	Cables	20%				100%
Lubrification	Metal scrap	100%				100%		0%				
Petroleum & other extraction	Industrial waste	80%	90%			10%	Metal scrap	20%				100%
PFAS gas uses	Metal scrap	30%				100%	Industrial waste	70%	90%			10%

* Include processes where the PFASs follow other materials (typically metals) for recovery of these materials

4.1.2 Solid waste pre-treatment

The PFAS restriction proposal notes that waste transfer stations may be sources of PFASs releases. Waste transfer stations are generally used to sort and crush bulk waste in order to enable efficient waste packing for further transport. The only study quoted in the PFAS restriction proposal is from China; the results may not be representative for the situation in the EEA, further described below.

The releases from solid waste pre-treatment are assumed primarily to be in the form of discharges to sewage treatment plants.

Danish investigation of sources. One Danish investigation of releases of PFASs with leachate from waste transfer and presorting stations has been identified. The sewage treatment company BIOFOS has undertaken source tracking of PFASs and other contaminants in the catchment area of their three sewage treatment plants: Lynetten, Damhusåen and Avedøre (DHI, 2023). The three plants in total receive sewage from 1.2 million inhabitants and several hundred companies in the capital region of Denmark. The results of the study are further described in section 4.2.1 while the focus in this section is on waste transfer and sorting systems. The highest concentration measured in discharges from companies was found in leachate from a storage area for scrap and waste. The ∑12 PFAS concentration in the leachate was 8.6 µg/L, about 280 times the average influent concentration in Danish sewage treatment plants. With a flow of 6,600 m^3/y, the total input to the sewage treatment plant was estimated at 57 g/y. From another storage area for metal sorting, the ∑12 PFAS concentration was determined to be 0.15 µg/L and the total flow to be 0.86 g/y. After leachate from landfills, leachate from waste transfer and presorting stations was by far the largest individual source type to BIOFOS's sewage treatment plants. No data are available to assess the size of the analysed sites compared to other similar sites in Denmark. The total number of relevant sites (both scrap sorting and other sorting of waste) has not been available for this study, but it is roughly assumed that the measurements of the two sites are representative of a total of 50 sites across Denmark. If each site releases a quantity comparable to the average of the two analysed sites, the total discharge to sewage treatment plants can be estimated at 1.4 kg/year. Considering that the ∑12 PFAS only represents a fraction of the total PFAAs and precursors, the total discharge to the sewage system is roughly estimated at 10 kg/y.

Geertinger et al. (2023) quote a Chinese study (Wang et al., 2020) that estimates that 0.0007 g PFASs per year is released to air from each of the investigated transfer stations, while 1.3 - 1.5 kg PFASs per year per site is discharged with leachate. Even if not necessarily representative of the EU situation, the data indicates that emission to the air is not a main release pathway for transfer stations.

Metal recycling. Bulson et al. (2023) performed a review of end-of-life circulation of PFASs in metal recycling streams. According to the review, European stormwater studies have shown that industrial runoff from metal recycling facilities can contribute to the releases of PFASs to the environment. Data for industrial runoff of PFASs was reported for stormwater from metal recycling facilities in Denmark and Lithuania (Nielsen et al., 2011[22]; Dudutyte et al., 2011 as cited by Bulson et al.). The Danish National Report provides a comprehensive evaluation of potential point sources of hazardous substances in the Copenhagen area (following the Control of Hazardous Substances in the Baltic Sea Region (COHIBA) framework), including industrial runoff from a shredder plant. Stormwater runoff samples were collected from two outlet locations onsite, which had stormwater controls (sand traps and oil traps) in place. Among the sites evaluated, the shredder plant was identified as a main source of PFASs (0.130-0.520

[22] This national report from the COHIBA project is no longer available from the internet.

µg/L). The measured concentrations were comparable to those from the BIOFOS source tracking study described above.

Bulson et al. (2023) furthermore notes that studies show that ELV (end-of-life vehicles) shredding processes may generate air emissions of PFASs as particulates. Kawecki et al. (2019, as cited by Bulson et al., 2023) found that high-density polyethylene, polystyrene, polyvinyl chloride, and light density poly-propylene outdoor air emissions (microplastics) were elevated due to ELV and WEEE shredding. The study did not measure PTFE or other fluoropolymers, but the results indicate that some releases of fluoropolymers or other PFAS particulates may be released from the shredders.

No data are available to enable the estimation of the releases of polymeric PFASs and TFA related PFASs by solid waste pre-treatment in Denmark. For the polymeric PFASs, the potential releases from waste pre-treatment are marked with a question mark, whereas for the TFA related PFASs, releases are considered to be insignificant as compared to releases from other sources.

4.1.3 Incineration

Fate of PFASs in municipal solid waste incinerators

The fate of PFASs by incineration has been reviewed recently for the Danish EPA by Geertinger and Jensen (2023).

The following paragraphs are translated from summarised conclusions by Geertinger and Jensen (2023) and reference is made to this report as concerns references to the original sources of the information: Based on laboratory tests and modelling, the PFASs should be totally destroyed under the temperature conditions in modern incinerators. In the most recent study reviewed, PFOA was the model substance. Furthermore, according to the review, the mechanism is the same as for the investigated short-chain model substances. At a temperature of 727°C, PFOA begins to release HF and form a short-lived α-lactone, which breaks down at 927°C and releases CO_2 to form 1-H-perfluoroheptane. Decomposition by pyrolysis and combustion of the ultra-short-chain (C2-C3) PFCA and PFSA showed that the thermal decomposition of TFA (C2) started at 427°C and was complete (99.9%) at 627°C. The decomposition of the analogous sulfonic acid (CF_3SO_3H) began at 377°C and was complete around 577 °C. The most important decomposition products during both combustion and pyrolysis were HF, SO_2 and CF_2O. The studies show that the functional group in PFOS decomposes before the perfluoroalkyl chain, and that PFOS and likely other similar PFAAs can be broken down in incinerators, which operate at temperatures that correspond to temperatures in conventional incineration plants in Denmark. Moreover, they show that PFOS cannot be converted into analogue PFSAs with shorter chains. In a later German study, PTFE was burned under typical waste incineration conditions to investigate whether PFAAs were formed in the process, which could then be discharged via the flue gas. PFOA was virtually the only PFAS that could be detected in the cleaned flue gas, but the concentration of PFOA was not different from the concentration in the control samples without the addition of PTFE, so no significant quantities of PFASs were formed.

Measurements from Danish incinerators

The results of measurements of PFASs in flue gas, residues and wastewater from two Danish municipal solid waste incinerators (MSWI) are summarized by Geertinger and Jensen (2023).

Furthermore, data on emissions to air have been provided for three MSWIs for the current study. No data has been available for hazardous waste incinerators.

PFASs have not been detected in the flue gas from any of the MSWIs. The limit of detection for flue gas is reported to be <0.006 µg/Nm^3 or lower for the individual PFASs. The detailed

data provided for the current study shows that the LOQ for the individual PFASs ranges from 0.0007 to 0.03 µg/Nm^3 and the ∑LOQ for 32 PFASs is 0.09 µg/Nm^3.

The measured concentrations in various media from one of the Danish incinerators in 2022 are shown in Table 76. For details about the measurements, reference is made to Geertinger and Jensen, 2023.

During the sampling of the flue gas, the PCC[23]-temperature was in the interval 960 - 1060 °C, and in the main part of the measuring period, the temperature was approximately 1000 °C. No PFASs were measured in the flue gas, plaster or fly ash.

The $PFAS_{22}$ concentration in wastewater was in the range of 12 - 26 ng/L. This is considerably lower than the concentration measured in another MSWI described in Geertinger and Jensen (2023) where the ∑12 PFAS in four samples were in the range 70 - 120 ng/L. PFBA, PFPeA, PFHxA and PFHpA were the only PFASs above the LOQ, with PFHxA present in the highest concentration.

Table 76. Measured concentrations in flows from a Danish incinerator for mixed MSW and industrial waste in 2022 (Based on Geertinger and Jensen, 2023)

Flow	n	LOQ	$PFAS_4$	$PFAS_{22}$	∑32 PFAS	Dominant PFASs
Water used for scrubber	10	<1 ng/L for individual PFASs	0.5 - 9.2 ng/L	3.2 - 27 ng/L	-	Not indicated
Plaster from scrubber	2	< 3.0 µg/kg d.w.	< LOQ	< LOQ	-	-
Waste water from scrubber	2	<1 ng/L for individual PFASs	1.5 - 1.8 ng/L	12 - 26 ng/L	-	PFBA, 6:2 FTS, PFPeA, PFBS og PFHxA
Bottom ash	1	< 0.1 µg/kg d.w.	0.04 µg/kg TS	0.57 µg/kg TS	-	6:2 FTS, PFBS, PFBA.
Untreated fly ash	1	< 0.1 µg/kg d.w.	< LOQ	< LOQ	-	-
Halozep treated fly ash	2	< 0.1 µg/kg d.w.	< LOQ	< LOQ	-	-
Flue gas	2	<0.006 µg/Nm^3 or lower fore individual PFASs	< LOQ	-	< LOQ	-

Data from the PULS database on direct discharges to surface water from sources other than sewage treatment plants, shown in Appendix 5, includes data on PFAS concentrations in flue gas cleaning water (1) or condensation water (3) from four incinerators with concentrations for ∑16 PFAS at 3.3 to 9.3 ng/L, slightly lower than the concentrations reported in the table above. From one of the facilities, furthermore, a concentration of 145 ng/L is reported for “process water” not further specified.

PFASs in bottom ash. Hyks and Hjelmar (2023) have recently analysed 13 samples of bottom ash collected from a representative selection of Danish MSW incinerator plants, representing approximately 80% of the incineration capacity in Denmark. The samples were ground to <0.1 mm and analysed for 22 PFASs. Apart from three individual PFAS measurements

[23] PCC: Postcombustion chamber

distributed across three different samples, the concentration of the individual PFASs was below the LOQ of 2.5 µg/kg d.w. (for PFUnDS and PFTrDS) or 0.5 µg/kg TS (for the rest). For ten of the samples, all measurements were below the LOQ. The study calculates the LOQ of $PFAS_{22}$ as half the sum of the LOQ of the individual PFAS; calculated using this methodology, the LOQ of $PFAS_{22}$ is estimated at 7.5 µg/kg d.w. For the three samples with measurements above the LOQ for individual PFAS, the $PFAS_{22}$ concentration of actually measured PFASs ranged from 0.55 to 1.62 µg/kg d.w. (i.e., measurements below LOQ were set at 0).

Measurements in incinerators in other countries

As limited results were available from incinerators in Denmark, more comprehensive studies in Swedish incinerators were used as background for the quantitative estimations.

Swedish survey. Strandberg et al. (2021) investigated PFASs in residues and condensate water in 27 (in total 31 furnaces) of 38 incineration plants in Sweden. In 26 of the furnaces included, both household and industrial waste were burned, of which household waste accounted for between 20 and 95% of the total. One furnace burned only household waste, two furnaces burned only industrial waste, while two furnaces burned household, industrial and hazardous waste. The study included 24 furnace lines with grate firing, which is the technology used in Denmark. For further details about the measurements, reference is made to Geertinger and Jensen (2023) and Strandberg et al. (2021).

Table 77. Arithmetic mean (average) and standard deviation for the sum of PFAS concentrations in all pooled samples from all plants, by PFAS group. For measurements below the LOD, values were replaced by half of the LOD before calculation (Strandberg et al., 2021).

Group (no of substances)	Bottom ash µg/kg		Condensate water ng/L		Fly ash µg/kg	
	Arithmetic mean	s.d.	Arithmetic mean	s.d.	Arithmetic mean	s.d.
∑PFCAs (12)	0.90	0.064	22	48	2.5	6.7
∑PFCAs precursor (6)	1.5	1.9	0.75	0	0.83	0.43
∑PFSAs (4)	0.30	0.31	1.3	1.9	0.54	1.2
∑PFSAs precursor (5)	0.59	0.30	2.5	0.57	1.7	4.1
∑27 PFASs	3.3	-	26.6	-	5.6	
LOD	0.1-0.2 for individual PFASs		0.1-0.2 for individual PFASs		0.1-0.2 for individual PFASs	

Single Swedish study. In a recent Swedish study (not included in Geertinger and Jensen, 2023) of PFASs in a MSWI in Northern Sweden, sampling was performed during incineration of two different waste mixes: Normal MSW and incineration of a waste mix with 5−8 wt % sewage sludge added to the MSW (referred to as Sludge:MSW). The overall results are shown in Table 78. The results of PFASs in flue gas are discussed below the table. Notably, the total PFASs in leachate from temporary waste stockpile was of the same magnitude as the total quantity of PFASs in residues and flue gas from the incinerator. The weight of the waste stockpile was 45,000 tonnes (Björklund et al., 2021).

Table 78. Estimated total outputs from an incinerator plant in Sweden incinerating 120,000 t waste per year (Björklund et al. 2023)

	MSW only		Mix of MSW and sewage sludge	
	Average concentration	Total annual quantity, g ∑18 PFAS	Average concentration	Total annual quantity, g ∑18 PFAS
Flue gas	4.7 ng/m^3	5	4.6 ng/Nm^3	4
Bottom ash	0.23 µg/kg	5	1.3 µg/kg	26
Air pollution control residues	n.d.	n.d.	1.1 µg/kg	7
Treated process water	70 ng/L	9	0.18 µg/L	4
Total from waste incinerator	-	19	-	41
Leachate from temporary waste stockpile	211 ng/L*	33 *	-	-

* Temporary waste storage of 40,000 t/y. Estimated on the basis of a previous study (Björklund et al. 2021). The LOQ in the flue gas varies by substance from 0.01 to 0.34 ng/m^3.

Very few measurements demonstrating PFASs in the flue gas from MSWIs have been identified in the literature. In the new Swedish study described above, total concentration of the sum of 27 PFASs was measured at 0.0046 - 0.0047 µg/Nm^3 (Björklund et al. 2023). The main contribution was from PFBA (0.0028−0.0038 µg/Nm³, LOQ: 0.00006 µg/Nm³), followed by PFHxA (0.00022−0.0019 µg/Nm³, LOQ: 0.00001 µg/Nm³) and PFOA (0.00016 - 0.00040 µg/Nm³, LOQ: 0.00003 µg/Nm³). PFBA alone accounted for about 70% of the total. The LOQ for PFBA (C4) in the available measurements in Danish MSWIs was 0.0008 µg/Nm^3. If the concentration was the same in the flue gas in these Danish MSWIs as in the Swedish MSWI, it should consequently have been measured as the concentration would be above the LOQ (i.e., the difference for this PFAS was not due to differences in detection levels). For PFHxA and PFOA (and other measured PFASs), the LOQ of the measurements in Danish MSWIs was higher than the measured concentrations in the Swedish incinerator. If the concentration was the same as in the Swedish MSWI it would consequently have been measured as <LOQ. It cannot be ruled out, however, that the high concentrations of PFBA as compared to all the other measured PFASs in the Swedish incinerator may be due to some specific sources of this substance in the waste.

In the absence of other measurements with concentrations above the applied LOQ, the data from the Swedish incinerator was used for the calculations in the present study in order to obtain an indication of the total quantities of PFAAs and precursors that may be emitted from Danish MSWIs. If, alternatively, half of the total LOQ of 32 PFASs measured in Danish incinerators are applied (available measurements), the total would be 0.01 µg/Nm^3, which represents the absolute maximum for the 32 PFASs. However, this number cannot be considered realistic. The Swedish data include 27 individual PFASs and may underestimate the total, as other PFASs may contribute, but no data on total extractable organic fluorine in emissions and residues from waste incinerators, which could indicate the potential underestimation, have been identified.

Ultra-short PFASs. The available measurements in neither Danish nor Swedish incinerators include measurements of concentrations of the ultra-short-chain C2 and C3 PFCAs (TFA and PFPrA). Aleksandrov et al. (2019) analysed waste incineration of PTFE in a German pilot plant to evaluate potential formation of PFASs in flue gas. The measurements included TFA but not PFPrA. No statistically significant evidence was found that the PFASs studied were created

during the incineration of PTFE. Geertinger and Jensen (2023) conclude that the results document that PTFE is destroyed by incineration at temperatures and residence times comparable to those applied in Danish incinerators.

Emission of PFAS gases. Among the reviewed studies is a literature survey from the Norwegian Institute for Air Research (NILU) on emissions from incineration of fluoropolymer materials (Huber et al., 2009). According to the survey, "*The main products of PTFE incineration at temperatures between 750 and 1050°C, relevant for Norwegian waste incineration plants, are CF_4 (PFC-14), CHF_3 (HFC-23), C_2F_6 (PFC-116), TFE and HFP*." Of these, "*HFC-23, PFC-116 and HFP fall under the PFAS definition"*. The survey concludes that data were not available for a quantification of the fluorinated gases from Norwegian incinerators and calls for studies on actual emission from incinerators.

A more recent review of environmental and health concerns of fluoropolymers from a number of leading experts (Lohmann et al., 2020) concludes that the effectiveness of incinerators to destroy PFASs and the tendency for formation of fluorinated or mixed halogenated organic by-products is not well understood. Furthermore, they note that PTFE can produce PFCAs (including TFA) and other fluorinated compounds when heated to temperatures between 250 °C and 600 °C, relevant for uncontrolled burning.

The review of Geertinger and Jensen (2023) does not include the fluorinated gases under the PFAS definition, and the formation of these gases are consequently not taken into account in the conclusions on the destruction efficiency of the PFAS. The review quotes several studies demonstrating that fluorinated gases (some fluorinated gases falling under the definition used in the PFAS restriction proposal) are formed by incineration of PFAS, and notes that there is some concern about the formation of the fluorinated gases among authorities and scientists.

Polymeric PFASs in residues. No data on polymeric PFASs in residues from incineration have been identified. Yang et al. (2021) have demonstrated that small amounts of microplastics may end up in the bottom ash, but PTFE or other fluoropolymers are not among the types of plastics identified. It cannot be ruled out that a small amount of polymeric PFASs may end up in the residues, but the total quantities are assumed to be negligible in this study.

Potential sources of PFASs for incineration

The table below summarises the estimated potential sources of PFASs disposed of to incineration in Denmark in 2021. The estimates are based on the total quantity of PFASs disposed of as solid waste, as estimated in section 2.2, and their distribution by waste disposal method, shown in Table 79 and Table 80.

The TULAC applications are estimated to account for about 56% of the total input to incinerators, with 14% contributed by food contact materials and packaging, while total waste from medical devices and the transport sector represents another 15%.

Table 79. Potential sources of PFASs in solid waste for incineration in 2021

Sources	Potential quantity in waste for incineration, t/year				% of total
	TFA related PFASs	Polymeric PFASs	PFAAs and precursors	Total PFAS	
Apparel	0	260	68	329	26%
Textiles, upholstery, leather, and carpets	0	308	68	376	30%
Food contact materials and packaging	0	138	40	178	14%
Metals plating/metal products	0	0.0	0.1	0.1	0.01%
Medical devices	0	79	27	106	8%
Transport sector	0	85	4	90	7%
Electronics & manufacture of semi-conductors	0	4	1	5	0.4%
Energy sector	0	14	1	15	1.2%
Construction materials/products	0	38	16	54	4%
Lubrification	1	0	0	1	0.1%
Oil-gas & other extraction	0	73	0	73	6%
PFAS gas uses	45	0	0	45	4%
Total	46	997	226	1,267	100%

Input, output and destruction of PFASs by incineration

Total quantities of waste incinerated and residues produced in 2021 in Denmark are shown in Table 80. The quantities of waste are used for calculation of the total emission of flue gas from the incinerators. The quantities represent all incinerators in Denmark, including 22 dedicated MSWIs, 4 multifueled (mix of waste and other fuels) and 3 specialized waste incinerators (of these, at least one is a dedicated hazardous waste incinerator). The available data do not allow for a distinction between MSWI and other incinerators; consequently, all outputs from incineration of waste in Denmark are aggregated. The quantities of waste are based on waste statistics from the Danish EPA (2023c), whereas the quantities of residues are based on Energinet.dk (2023), which differentiates between residues from energy production based on incineration of waste and residues from other fuel consumption.

Table 80. Total quantities of waste incinerated and residues produced in 2021 *

	Quantity, t/y	Source
Total waste received for incineration **	3,233,000	Danish EPA (2023)
- of this total waste from Danish sources	2,815,000	Danish EPA (2023)
- of this municipal solid waste	1,861,000	Danish EPA (2023)
- of this hazardous waste	192,000	Danish EPA (2023)
- of this Imported waste for incineration (excl. specialised incineration)	406,000	Danish EPA (2023)
Produced bottom ash from waste incineration	600,514	Energinet.dk (2023)
Produced flue gas treatment products (RGA)	90,963	Energinet.dk (2023)

* Incudes 22 dedicated MSWs, 4 multifueled and 3 specialized waste incinerators.

** Numbers do not add up exactly; the quantity reported in the statistics is used for estimation of total amount of flue gas generated.

The quantity of flue gas generated per tonne of waste incinerated varies among the incinerators. According to Nielsen et al. (2007), on average, the MSWIs generated 6,000- 6,400 Nm³/t incinerated waste in 2007. In the absence of a newer average value, a value of 6,200 Nm³/t incinerated waste is applied here.

No data on total quantity of treated wastewater from Danish incinerators have been available. Considering the estimated small quantities of PFASs in the wastewater, no effort has been made to collect specific information on wastewater quantities from incinerators in Denmark; instead, a value of 0.43 m^3 per tonne waste is applied based on Björklund et al. (2023). In fact, only incinerators with wet flue gas cleaning generate wastewater. Therefore, the total will be overestimated.

Flue gas treatment products are nearly 100% exported for special deposition abroad[24]. In 2021, an export of 70,000 tonnes was reported (Danish EPA). The exported quantities vary considerably from year to year due to temporary storage. However, it is assumed in this study that in 2021, all flue gas treatment products ultimately were exported. Therefore the export was allocated to the reference year 2021.

Concentrations of TFA related substances. As described above, some PFAS gases may be emitted from incinerators, but it has not been possible to identify any data usable for quantification. Furthermore, no measurements of TFA in residues from incinerators have been identified.

Concentrations of fluoropolymers. No data on fluoropolymers in flue gas, residues or wastewater is available. Whereas fluoropolymers may generate some PFAS gases by the incineration process, it is assumed in this study that the presence of fluoropolymers in flue gas, residues or wastewater are negligible (indicated as “negl.” in summaries)**.**

Concentrations of PFAAs and precursors. The applied concentrations of PFAAs and precursors in emissions, residues and wastewater are summarised in Table 81. As described for leachate from landfills and sewage waste, the measured target PFASs may not represent the total concentration of PFAAs and precursors; however, no data have been available on total extractable organic fluor (EOF), or data on other PFAA precursors. Consequently, the available measured concentrations were applied as best estimates.

[24] https://www.drh-amba.dk/restprodukthandtering/

Table 81. Applied concentrations of PFAAs and precursors

	Concentration	Source
Emission to air	0.0047 µg/Nm^3	Björklund et al., 2023.
Discharges with waste water	26.6 ng/L	Strandberg et al., 2021. Results for two Danish incinerators were lower and higher, respectively.
Bottom ash	3.3 µg/kg d.w.	Strandberg et al. 2021. Danish data shows 0.55-1.62 µg/kg d.w of quantified PFAS. The sum of half of the LOQ of individual PFASs is 7.5 µg/kg d.w (Hyks and Hjermar, 2023). The Swedish study used a lower LOQ. These data are consequently used as a best estimate in this study.
Flue gas cleaning products	5.6 µg/kg d.w.	Strandberg et al., 2021. Danish measurements of PFASs in fly ash from one incinerator were below LOQ.

The potential input, output and destruction of PFASs by incineration in Denmark are summarised in Table 82. The general methodology applied in this study of dividing the PFASs into three groups is actually not applicable for incineration, as the polymeric PFASs may potentially form PFASs included in the other two groups (mainly the TFA related PFASs). However, as no data are available to quantify the generation of PFASs in the other groups, no attempt of adjusting the methodology has been attempted.

Destruction efficiency. The calculated destruction efficiency for PFAAs and precursors can be estimated at 99.9989% on the basis of the available data**.** Geertinger and Jensen (2023) do not indicate destruction efficiencies from Danish MSWIs, but mention that under the conditions used in the incinerators, the destruction efficiency for other persistent organic halogen compounds is 99.99%. Even though the estimate is uncertain**,** the available data indicate that the destruction efficiencies for PFAAs and precursors are quite similar to the efficiencies for other persistent organic halogen compounds, whereas the extent to which PFAS gases may be formed by incineration of PTFE and other fluoropolymers remains uncertain.

Based on the available data described above, the total content of PFAAs and precursors in emissions to air, wastewater and residues is estimated at 2.6 kg. This is well in accordance with Björklund et al. (2023), which estimates a total of 41 g ∑18 PFAS released per year from a Swedish incinerator with a 120,000 t/y capacity. Of this, emissions to air were approximately 5 g/y.

Table 82. Potential input, output and destruction of PFASs by incineration in Denmark

	TFA related PFASs	Polymeric PFASs	PFAAs and precursors
Total input, kg/y	416,481	839,338	248,432
Emission to air, kg/y	n.d.	Negl.	0.09
Discharges with waste water, kg/y	n.d.	Negl.	0.04
Bottom ash, kg/y	n.d.	Negl.	1.98
Flue gas cleaning products (exported), kg/y	n.d.	Negl.	0.51
Destroyed, kg/y *	416,481 (minus n.d.)	839,338 **	248,430

* "Destroyed" means transformation where the transformation products are not themselves PFASs in this study.

** The open question is whether incineration of polymeric PFASs may lead to formation of some PFAS gases.

n.d.: no data. Negl.: No data, but considered negligible.

4.1.4 Landfilling in Denmark

Landfilling generally does not destroy PFASs in waste streams. It is assumed that over time, close to 100% of all contained PFASs or their degradation products will eventually end up in leachate, be released to air or seep into the underlying ground.

The PFASs released from landfills today originate from waste disposed to landfill over many years, and the PFASs disposed to engineered landfills today will ultimately be released over a time horizon of hundreds of years. The current study estimates that releases today from controlled landfills which is significantly below the actual quantities disposed of to engineered landfills today. The methodology is different from the approach in the PFAS restriction proposal, where ultimate releases from the waste disposed of currently are used for modelling.

In Denmark, more than 4,000 locations are known where waste has been landfilled. The locations make up a total area of around 143 km^2, corresponding to 0.3% of Denmark's total land area (Clausen and Kalvig, 2020). Most of these sites are not supervised and the waste may largely originate from a time before the use of PFASs became widespread. No data are available on PFASs accumulated in uncontrolled old landfills and waste dumps and no data are available on the releases from these sites to the surroundings. As for other contaminated sites, the eventual fate of the substances is outside the scope of current substance flow analysis which includes only releases from controlled landfills.

PFAAs and precursors in leachate from landfills

The Danish EPA is the authority for 151 controlled landfills in Denmark (Danish EPA, 2023h). Of the 151 controlled landfills, 55 are currently receiving waste, as shown in Table 83.

Table 83. Types of 151 landfills in Denmark under the authority of the Danish EPA (2023h)

Type	Total	Active (receiving waste)	Controlled, but not receiving waste
Non-specialised landfills	99	26	73*
Special landfills	28	9	19
Soil deposits	2	1	1
Dredged marine sediments deposits	22	19	3
Total	151	55	96

*Of these, 33 old landfills were not covered by the provisions of the Danish Statutory Order on landfills (BEK nr 1253 of 21/11/2019); i.e., they are not necessarily equipped with liner and leachate collection.

For the engineered landfills still receiving waste for disposal, the Energy Agency prepares benchmarking reports which indicate the extent to which the leachate is treated outside the landfill.

The most recent benchmarking report, BEATE 2021, includes 40 engineered landfills [Danish: deponeringsanlæg] still receiving waste (Viegand Maagøe, 2021). From the engineered landfills still in operation, data from the benchmarking system shows that the leachate from 22 of 24 facilities (some landfills have more than one facility) for mixed waste is treated outside the facility, which is interpreted as “the leachate is discharged to sewage treatment plants” in the case of this study. For facilities for inert, mineral and hazardous waste, only 17 out of 22 facilities discharge the leachate for treatment outside the facility, whereas the remaining manage the leachate within the facility. For 7 facilities treating leachate within the facility, three employ mechanical and/or chemical treatment, one a root zone system, one seepage to the marine environment and one discharges to a lagoon.

From the Danish EPA, a list with 151 controlled engineered landfills has been obtained. As shown above, these 151 facilities cover a range of different landfills. PFASs may not be present in leachate from all of the facilities. The concentration of $PFAS_{22}$ in leachate is reported for 54 controlled landfills, as summarized in Table 84. As illustrated by the ranges and standard deviations, the concentration of PFASs in leachate varies significantly. For 6 of the 54 facilities, quantities of leachate are not reported, and they are consequently not included in the flow-weighted average. It is not indicated how many of the facilities with reported PFAS concentrations are categorized as still in operation, engineered landfills (in accordance with the provisions of the Danish Statutory Order on landfills) or old landfills. The total quantity of leachate from the 75 of the 150 landfills with data on leachate volumes in the list from the Danish EPA is 2.2 million m^3/year, while PFAS data are available from landfills with a total leachate volume of 2.6 million m^3/year. According to the Danish EPA, approximately 90% of the leachate for which the agency has data is collected and discharged to sewage treatment plants.

A list of Danish sources having direct discharge to surface water in Appendix 5 includes concentrations of ∑16 PFAS from 7 engineered landfills with an average concentration of 0.058 µg/L. The water discharged directly to surface water is typically not leachate, but surface water or pumped groundwater.

In the absence of data on the fate of discharges from Danish landfills, it will be assumed that 2.0 million m^3/year is discharged to the sewage treatment plants for this study.

Table 84. Available measurements of PFASs in leachate from Danish controlled landfills

	Number of facilities with PFAS data	Total leachate represented by PFAS data million m^3/year	Arithmetic mean µg/L	Range, µg/L	s.d. µg/L	Flow weighted mean, µg/L
$PFAS_{22}$	54	1.6	3.3	0.07 - 39.9	7.0	2.8
$PFAS_4$	54	1.6	0.6	0.02 - 4.2	0.8	0.4

No overview of the PFAS profiles in the leachate from Danish engineered landfills is available. Data obtained from a few engineered landfills as part of stakeholder consultation show varying PFAS profiles between the landfills. Data from Sweden may be used to indicate the average profiles, as the waste landfilled may be quite similar to the waste landfilled in Denmark. Of 34 PFASs measured in leachate from 117 landfills in Sweden, the dominant target PFASs, calculated as mean values, were the following in decreasing order: PFBA, PFBS, PFHxA, PFPeA, PFOS, PFHpA and PFOA (Miljösamvirkan, 2022).

Diffuse releases of leachate from landfills to the environment

The majority of the collected leachate is currently directed to municipal SPTs. From old landfills without bottom membranes, PFASs may sieve into the surroundings. According to Bennedsen et al. (2017), the transport pathway for pollutants from a landfill toward surface water and/or groundwater depends on the landfill's typology. Surface runoff/internal runoff of leachate and drain runoff could lead to the transport of pollutants to surface water. Outflow of leachate via, e.g., leaky membrane could lead to the transport of pollutants to groundwater and surface water (Bennedsen et al. 2017). The methodology of the current substance flow analysis does not include groundwater as a receiving environmental compartment. All PFASs released to the groundwater and surface water are consequently allocated to surface water in this analysis.

Bennedsen et al. (2017) have measured PFASs in leachate and leachate affected groundwater from seven closed landfills. The concentration of ∑12 PFASs ranged from <0.001 µg/L to 2.82 µg/L with an average of 0.6 µg/L. It is not reported as to which measurements concerned leachate and which concerned leachate-affected groundwater; therefore, a comparison with the concentrations reported from the controlled landfills above is not possible. On this basis of the measurements, Bennedsen et al. (2017) concluded that "*Bisphenol A and partly PFAS-compounds have been detected at low levels that possibly may pose a threat towards surface waters in the immediate vicinity of landfills*".

An example of PFASs in leachate from a closed landfill in Denmark is shown in the table below. The cells were constructed without a bottom membrane; therefore, part of the leachate may be released directly to groundwater. The results demonstrate levels well above the mean values for engineered landfills in Denmark shown above, both from cells with mixed waste and cells with shredder waste. The quantities of leachate discharged to the municipal sewage treatment plant and discharged directly to the environment were not reported; therefore, total discharged quantities of PFASs cannot be calculated.

Table 85. PFAS concentrations in leachate from different types of cells and in leachate discharged to a municipal sewage plant in Denmark (Source: Confidential stakeholder input)

Waste type landfilled in cell	Number of cells	$PFAS_4$ in leachate µg/L	∑12 PFAS in leachate µg/L
PCB waste	1	0.4	8.1
Mixed waste	4	0.03-0.9	3.6 - 59.9
Shredder waste	2	0.62-0.62	13.4 - 19.2
Leachate discharged to municipal sewage plant		0.4	29.9

As mentioned in Table 83, 33 old non-specialised landfills, accounting for 1/3 of controlled non-specialised landfills, are not covered by the provisions of the Danish Statutory Order on landfills (BEK nr 1253 of 21/11/20219). From these landfills, a significant part of the leachate may sieve into the surroundings.

In the absence of actual data on leachate sieving from landfills, it was assumed that half of the leachate may be released directly to the surroundings from the 33 old landfills not covered by the provisions of the Danish Statutory Order on landfills. If the amount of leachate per landfill is assumed to correspond to the average of the reporting landfills (about 22,000 m³/year), the total quantity released directly to the environment can be estimated at 359,000 m³/year. If the concentration is assumed to be similar to the average reported average concentration of leachate discharged to sewage treatment plants (Table 84), the total releases can be estimated at 2.4 kg for total PFAAs and precursors and 0.2 for $PFAS_4$. No data on releases of TFA related substances are available, but the concentrations are assumed to be the same as for leachate directed to STPs.

Reported direct discharges to surface water from landfills

Data on reported direct discharges to surface water from landfills are shown in Appendix 5. The total discharges from 8 landfills with reported direct discharges to surface water was 0.066 kg/y for ∑16 PFAS and 0.034 for $PFAS_4$. As for the discharges from landfills to sewage treatment plants, ∑16 PFAS is multiplied by 2 to estimate total PFAAs and precursors.

Review of literature on measured PFASs vs. extractable organic fluorine (EOF)

Measurements of target PFASs and total extractable organic fluorine (EOF) indicates that the total PFAS concentration in the leachate is higher than the concentration of target PFASs. The term “target analyses” refers to analyses of specific PFASs ,whereas EOF analysis is non-specific. None of the data sources used for this substance flow analysis has included measurements of total oxidizable precursor (TOP).

Side-chain fluorinated polymers. Fredriksson et al. (2020), in a pilot study of the side-chain fluorinated polymer component of Scotchgard™ products and their levels in STP sludge and landfill leachate from Sweden, found detectable levels of pre-2002 Scotchgard products in three of the five analysed landfill leachate samples, but at very low levels. Scotchgard™ is a brand name of water- and dirt repellents for apparel and textiles produced by the company 3M. Before 2002 it was based on side-chain fluorinated polymers with PFOS related side-chains; after 2002, it was based on similar polymers, but with shorter PFASs related side-chains. Post-2002 products were not detected in any of the landfill leachates. The authors suggest that the explanation for the low levels (as compared to levels in sewage sludge described in section 4.2.3) could be that both compounds are strongly sorbed to particles, and they consequently do not end up in the leachate. For both the sludge and leachate samples, the quantified levels of pre-2002 and post-2002 Scotchgard products only contributed to a minor fraction of the EOF. Compared to the sludge samples, a relatively higher amount of target PFASs were detected in the landfill leachate particles, where ∑93 PFAS contributed to 14 - 30% of the EOF

(as compared to sewage sludge, where the detectable PFASs contributed up to 4% of the EOF). In contrast, pre-2002 and post-2002 Scotchgard products only contributed up to 0.03% of the EOF in the leachate. The extent to which $PFAS_{22}$ contributes to ∑93 PFAS and the EOF is not indicated. The target PFASs vs. EOF in sewage sludge is further discussed in section 4.2.3.

TFA related substances in leachate. Björnsdotter et al. (2019) studied ultra-short-chain PFAAs in leachate from Swedish firefighting training sites, landfills, and a hazardous waste management facility (the facility is not further described). This description focuses on the landfills. The average concentration of ∑29 PFAS in 7 leachate samples from three municipal and industrial landfills was 4.4 µg/L. Of this, TFA accounted for 55% (2.4 µg/L) on average, while the total of four other ultra-short-chain PFASs (PFPrA, TFMS, PFEtS, and PFPrS) accounted for 11% in total. The 29 PFASs encompassed similar PFASs as $PFAS_{22}$ plus the five ultra-short-chain PFASs and some telomers. The total average concentration of the ∑24 PFAS (excluding the 5 ultra-short-chain) was 1.5 µg/L, lower than the average $PFAS_{22}$ in leachate from Danish engineered landfills at 3.3 µg/L (Table 84). The average concentration of TFA in leachate and stormwater from the Swedish landfills was 1.6 times the concentration of ∑24 PFAS. In the absence of other data, this ratio was used as a best estimate of TFA in leachate from Danish landfills. In two stormwater samples from the Swedish landfills, TFA accounted for an even higher percentage, likely due to TFA in stormwater, as the TFA concentration in the leachate was only slightly higher than the concentrations in rainwater reported for Germany in section 5.1.2.

TFA formation by biodegradation. Sun et al. (2020) demonstrated formation of TFA by biodegradation of a number of PFASs such as 6:2 FTOH,4:2FTOH and TFMAA, and suggested that biodegradation of fluorochemicals is an overlooked source of TFA and that there are still some unspecified mechanisms of TFA production pathways.

Potential sources of PFASs for landfilling

The total quantities of waste (excl. soil) disposed of to engineered landfills in Denmark in 2021 were 330,000 t (Danish EPA, 2023c).

Table 86 below summarises the estimated potential sources of PFASs disposed of to engineered landfills in Denmark in 2021. The estimates shown are based on the total quantity of PFASs disposed of as solid waste, as estimated in section 2.2, and their distribution by waste disposal method (Table 74 and Table 75). The contributions considered from the transport sector are shredder waste, whereas the contributions from construction products and materials are mineral wastes with coatings, sealants, etc. with PFAS contents. From the energy sector the waste includes landfilled wind turbine blades.

The total quantity of 46 t/y disposed of today will ultimately be released to the environment or directed to sewage treatment plants with leachate over many years. The experience with more than 4,000 locations where waste has been deposited in the past is that they have turned into highly polluted sites: hot spots from which pollutants are dispersed into the surroundings.

Table 86. Potential sources of PFASs in solid waste for engineered landfills in Denmark

Sources	Potential quantity in waste for engineered landfills t/year				% of total
	TFA related PFASs	Polymeric PFASs	PFAAs and precursors	Total PFAS	
Transport sector	-	37	2	38	83%
Energy sector	-	4	-	4	8%
Construction materials/products	-	-	4	4	9%
Total	-	40	6	46	100%

Total estimated PFASs in leachate and other discharges from landfills

The total discharge of PFASs from Danish landfills to sewage treatment plants is summarised in Table 87. The available data indicate that the specifically measured PFASs account for a significantly higher fraction of the EOF in leachate in comparison with sewage water and sewage sludge. The total concentration of PFAAs and precursors is roughly estimated by multiplying the $PFAS_{22}$ concentration by 2.

For $PFAS_4$, the total quantity discharged to STPs of 1.2 kg/y represents approximately 24% of the estimated $PFAS_4$ content of 5.0 kg/y in influent to the STPs (Table 97). A similar comparison is not possible for $PFAS_{22}$, as the data for PFASs in influents is only available for ∑16 PFAS.

Table 87. Estimated discharge of PFASs with leachate from Danish landfills to sewage treatment plants

Substances	Discharges to sewage treatment plants		
	Total leachate million m^3 / year	Average concentration µg/L	Discharges kg/y
$PFAS_{22}$ *	2.0 *	3.3 *	6.6
$PFAS_4$ *	2.0	0.6 *	1.2
Total PFAAs and precursors **	2.0	6.6 **	13.2
TFA related PFASs **	2.0	5.3 **	10.6
Polymeric PFASs	n.d.	n.d.	n.d.

* Derived on the basis of the data from the Danish EPA in Table 84.

** Derived on the basis of the reviewed literature

n.d.: No data

The estimated releases of PFASs from Danish landfills to surface water, divided by leachate sieving to the surroundings and direct discharges to surface water, are summarised in Table 88.

Table 88. Estimated releases of PFASs from Danish landfills to surface water

Substances	Leachate sieving to surface water ***			Direct discharges to surface water ****			Total releases kg/y
	Total release million m^3 / year	Average concentration µg/L	Releases kg/y	Total discharge million m^3 / year	Average concentration µg/L	Releases kg/y	
$PFAS_{22}$ *	0.4	3.3	1.2	0.5	0.13	0.07	1.3
$PFAS_4$ *	0.4	0.6	0.2	0.5	0.06	0.03	0.2
Total PFAAs and precursors **	0.4	6.6	2.4	0.5	0.26	0.13	2.5
TFA related PFASs **	0.4	5.28	1.9	0.5	0.21	0.10	2.0
Polymeric PFASs	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.

* Derived on the basis of the data from the Danish EPA in Table 84.

** Derived on the basis of the reviewed literature

*** All releases to the surroundings from the landfill are allocated to releases to surface water in this study

**** Based on the data in Appendix 5

n.d.: No data

For comparison, Knutsen et al. (2019) estimated the total national ∑28 PFAS discharges to the STPs and the environment from landfills in Norway at 17 ± 29 kg/year and note that this is in the same *per capita* range as reported discharges from landfills in the USA, China and Germany. They report that 55% of the leachate from the Norwegian landfills is discharged to STPs and 45% to the environment. Due to differing geographies, the distribution between discharges to STPs and releases to the environment are not expected to be similar in Norway and Denmark.

Emission to air from landfills

A number of studies have demonstrated emission of PFASs to air from landfills.

Canadian study. PFASs were determined by Ahrens et al. (2009) in air over two landfill sites and a sewage treatment plant (STP) in Canada in summer 2009. Both landfills investigated had processes in place for capturing landfill gas and further reduced volatilization to air by keeping the active, exposed area to a minimum by covering the waste with soil and a plastic film. The engineered landfills were still in operation and the type of waste deposited at the two landfills was similar, mostly residential waste. The samples were analysed for five PFAS classes to investigate their concentration in air, composition, and emissions to the atmosphere. ∑18 PFAS concentrations in air were 5-10 times higher at the landfill sites (2,780-26,430 pg/m^3) compared to reference sites (597-1,600 pg/m^3). The volatile FTOHs were the predominant PFAS class in air for the landfill sites, with 8:2 FTOH as the dominating PFAS (1,290-17,380 pg/m^3). Contrary to this, 6:2 FTOH was the dominant PFAS over the STPs, indicating that the sources of the FTOH in the landfill are older than in the sewage treatment plants, as the longer-chain 8:2 FTOH has been replaced by the shorter-chain 6:2 FTOH over the years. ∑18 PFAS yearly emissions estimated using a simplified dispersion model were 0.099 kg/y for landfill site 1, and 1.0 kg/y for landfill site 2. The study did not compare the estimated emission to air with the discharges with leachate, which otherwise could be used to assess how the data could be applied to the Danish situation. But as mentioned above, the *per capita* discharges from landfills in the USA, China, Germany and Norway are in the same range, and the current data indicates that this may be the case for landfills in Denmark. No data for Canada were available.

German study. Weinberg et al. (2011) have demonstrated elevated concentrations of PFASs over two landfills in Germany as compared to reference sites and concluded that the concentration was higher over active engineered landfills than over closed. Total neutral ∑16 neutral PFAS concentrations ranged from 84 to 706 pg/m^3 at the landfill sites. Of the neutral PFASs at the closed landfill, FTOHs were detected in highest proportions (>75%), followed by FASE/FTA (about 6% each) and FASA (5%). At the active site, FTOHs accounted for an even higher percentage of the total neutral PFASs (>92%). Ionic PFASs were detected in all particle-phase samples, with ∑9 ionic PFASs ranging from 6 to 42 pg/m^3 over the landfills. PFBA was the predominant ionic PFAS with average proportions of 59%, followed by PFHxA (16%), PFOS (11%) and PFOA (9%). In contrast to particle-bound PFASs, where there was no difference between landfill and reference sites, air concentrations of volatile and semi-volatile PFASs were 1.5- 3 times higher over landfills than at corresponding reference sites. The authors note that the results suggest that these compounds are subject to volatilisation from products disposed at landfills. The study does not estimate the potential emissions from the landfills.

Study from the USA. Titaley et al. (2023) measured 25 target neutral PFAS, including fluorotelomer alcohols (FTOHs) and five other PFAS classes, in landfill gas from a gas well or header pipe. Fluorotelomer alcohols were found at the highest levels, ranging from 830,000−4,900,000 pg/m^3, approximately 2 orders of magnitude higher than FTOH levels reported in ambient air collected near landfills. The authors conclude that the data confirm landfill gas as the likely origin of FTOHs and 6:2 FTAc found in air near landfills and indicate that landfills are also sources of 12:2 FTOH.

Review from USA. The significance of emissions to air from landfill is confirmed by a critical review of PFAS landfill disposal in the USA (Tolaymat et al., 2023) that concludes that the amount emitted with landfill gas is approximately half the amount released with leachate.

Conclusion. In conclusion, if it is assumed that the emission from each of 150 Danish landfills was in the range of 0.1 - 1 kg/year, total emissions of PFAAs and precursors would be 15 - 150 kg. Considering that the majority of the landfills have been closed for many years and the landfills generally do not receive municipal solid waste (e.g. with TULAC as major sources of PFAS), it is assumed that the actual emissions are most likely on the low end of the estimate. Consequently, an emission of 25 kg/y for PFAAs and precursors was applied as best estimate. The estimate is considered very uncertain. Notably, this quantity is higher than the estimated discharge with leachate to sewage treatment plants (STPs). Even though the estimate is uncertain, it clearly indicates that the emission to air from landfills is likely significantly higher than emissions from incinerators, where the total emission is estimated at 0.1 kg/y.

Potential input and output of PFASs to/from landfills

The potential input and output of PFASs to and from landfills in Denmark is summarised in the table below.

The PFAS restriction proposal estimates a potential EEA emission from landfills at 1.14-5.72 t/y. On a *per capita* basis, this would correspond to emissions of approximately 10 - 50 kg/y from landfills in Denmark. The quantified released from landfills Denmark is within this range.

Table 89. Potential input and output of PFASs to/from landfills in 2021

	TFA related PFASs kg/y	Polymeric PFASs kg/y	PFAAs and precursors, kg/y
Total input	n.d.	36,562	5,836
Released to air, kg/y	n.d.	Negl	25
Discharged with leachate to sewage treatment plants, kg/y	10.6	Negl	13.2
Released to surface water, kg/y	2.0	Negl	2.5
Accumulated in landfills, kg/y	n.d.	36,562	5,795

n.d.: no data. Negl.: No data but considered negligible.

4.2 Presence and fate of PFASs in sewage management

4.2.1 Sources of PFASs in sewage

No overview of sources of PFASs in sewage has been available for this study. The following section combines information from section 2.2 on potential quantities of PFASs discharged to the sewer system from production and use of products, with estimates of other sources such as leachate from landfills, human excretions (from food sources), leachate from waste pre-handling, and rainwater.

Danish studies on source tracking of PFAS

One detailed Danish study on source tracking of PFASs and other contaminants in the catchment area of sewage treatment plants has been identified. The results are summarised in Table 90. The sewage treatment company BIOFOS has undertaken source tracking of PFASs and other contaminants in the catchment area of their three sewage treatment plants: Lynetten, Damhusåen and Avedøre (DHI, 2023). The three plants receive sewage from 1.2 million inhabitants in total and several hundred companies in the capital region of Denmark. The plants receive about 1/4 of all sewage in Denmark. Samples were collected from the discharges of 30 companies; for 21 of these companies, 12 PFASs[25] were analysed. For most of the samples, Sorbicell™ passive samplers were used. Total discharges from the individual sources analysed for PFASs were 493,000 m^3, as compared to total influent to the three plants of 115 million m^3; i.e., the analysed sources represented 0.4% of the received sewage.[26]

The ∑12 total PFAS content in the discharges from the analysed sources was 344 g/year. The total PFAS content of discharges to the three sewage treatment plants was not reported. If it is assumed that the ∑16 PFAS concentration in the influent to the three plants was similar to the average of 30.4 ng/L (0.0304 µg/L) in 36 Danish sewage treatment plants summarised in Table 93, the 115 million m^3 would contain approximately 3.4 kg and the analysed sources would represent 10% of the total input of measured PFASs to the sewage treatment plants. The number of companies of each type in the catchment area was not reported, but in this study it is estimated that the contribution to the three STPs from the types of companies included may be significantly more than 10%.

A comparison with the total content in the plants' influent and effluent was carried out for PFOS only. The results from the measurement program indicate that leachate from waste landfills and surface runoff from storage sites for waste, scrap and metal are significant sources for the supply of PFOS to BIOFOS' three sewage treatment plants. Thus, two companies make up approx. 40% of the supply of PFOS to one of the treatment plants. If the results

[25] 12 PFASs: PFBA, PFBS, PFPeA, PFHxA, PFHxS, PFHpA, PFOA, PFOS, 6:2 FTS, PFOSA, PFNA, PFDA.

[26] https://biofos.dk/media/glpd31s3/bilag-1-kommentarer-til-milj-data_milj-beretning-2021.pdf

from the measurement program are extrapolated to the rest of the catchment area covered by BIOFOS, then more than 100% of the supply of PFOS to the treatment plants can be explained by these source types (DHI 2023). This conclusion cannot be extrapolated to the other PFASs, as the use of PFOS has been banned for many years and PFOS-containing waste in landfills will continue to be a source for many years after a ban, whereas other sources of PFOS will decrease faster.

PFOA was measured at concentrations above the LOQ in the discharge from 23 of the 24 companies, followed by PFHxA (16), PFBS (14), and PFHpA (14). The highest concentration of a single PFAS was a concentration of PFOS at 7.3 µg/L in leachate from a waste sorting facility. PFOS accounted for about 80% of the total PFASs from this source, indicating the presence of a specific source of PFOS in the sorted waste.

For the ∑12 PFAS, leachate from waste landfills and surface runoff from larger storage volumes of waste and scrap formed the most significant contributions.

The largest contribution among the analysed sources came from leachate from an engineered landfill in operation, which represented 80% of the total ∑12 PFAS discharge from the analysed sources. The concentration in leachate from the landfills ranged from 0.14 to 3.64 µg/L for ∑12 PFAS, with the higher concentration in leachate from the engineered landfill in operation, which also had the highest flow. The concentrations are well in accordance with the $PFAS_{22}$ concentrations reported for 54 landfills in Table 84, for which an arithmetic mean of 3.3 µg/L and a flow weighted average of 2.8 µg/L is estimated.

The highest concentration was found in leachate from a storage area for scrap and waste. The ∑12 PFAS concentration in the leachate was 8.6 µg/L, which is about 220 times higher than the average influent concentration measured in Danish sewage treatment plants. With a flow of 6,600 m^3/y, the total input to the sewage treatment plant was estimated at 57 g/y.

For containment systems for lowering groundwater level (usually made to reduce releases of contaminants in the affected area), pretreatment with carbon filters to lower the total ∑12 PFAS concentration was demonstrated as a significant mitigation possibility. Without carbon filters, these sources may contribute significant discharges.

The concentrations in discharges from two fire training grounds were relatively small (0.004 µg/L), but the extent to which PFAS-containing fire-fighting foams have actually been used on the training grounds was not reported.

PFAS-containing foams have been used only for some type of fires and PFAS-free foams were used on most training sites by 2021 (Henriksen et al., 2023).

Table 90. Concentration of ∑12 PFAS and total quantity of ∑12 PFAS in discharges from various sources in the catchment area of the three sewage treatment plants owned by BIOFOS (DHI, 2023)

Source	Flow m^3/year	Sampling technique	Concentration, ∑12 PFAS µg/L	Discharge of ∑12 PFAS g/year
Engineered landfill 1, active	120,000	Sorbicells	1.00	278
	120,000	Flowprop. 24-h test	3.64	
Old landfill 2, active until 1984	6,000	Random sample	1.12	3.8
	6,000	Random sample	0.14	
Old landfill, closed (year not indicated)	3,300	Random sample	0.05	0.2
Landfill for bottom ash	2,500	Sorbicells	0.005	0.01
Metal sorting - storage area for scrap and waste	6,600	Sorbicells	8.60	57
Metal sorting - storage area for scrap and waste	5,700	Sorbicells	0.15	0.86
Asphalt factory 1	7,200	Sorbicells	0.002	0.01
Asphalt factory 2	4,100	Sorbicells	0.004	0.02
Industrial laundry	29,000	Sorbicells	0.003	0.08
Car wash hall	1,600	Sorbicells	0.02	0.03
Car wash hall, cleaning	200	Sorbicells	0.19	0.04
Truck wash	390	Sorbicells	0.005	0.002
Bus wash	400	Sorbicells	0.008	0.03
Train wash 1	800	Sorbicells	0.07	0.06
Fire station 1, fire training ground	50	Sorbicells	0.004	0.0002
Fire station 2, fire training ground	550	Sorbicells	0.004	0.002
Prevention system 1 / groundwater lowering	16.500	Sorbicells	0.001	0.02
Prevention system 2/ groundwater lowering. Before coal filter	850	Random sample	0.29	0.25
Prevention system 2/ groundwater lowering. After coal filter	850	Random sample	0.09	0.08
Prevention system 3/ groundwater lowering. Before coal filter	700	Random sample	0.17	0.14
Prevention system 3/ groundwater lowering. After coal filter	850	Random sample	0.02	0.01
Groundwater lowering	175,000	Random sample	0.02	3.8
Total analysed sources	493,000			344

A recent report for the Danish EPA on source tracking of PFASs and other contaminants in test catchment areas concludes that sewage from an industrial area with district heating, car scrapping, a recycling station, waste sorting, metal processing, and other activities in particular contributed significantly to the $PFAS_4$ and $PFAS_{22}$ in the influent to the sewage treatment plants. The individual sources were not quantified (Pedersen et al., 2023). As regards TFA, a fire station was identified as a significant source.

Estimated sources of PFASs to sewage

The estimated sources of PFASs to sewage are summarized in Table 91. The main part of the table is based on the description of uses in section 2.2 and the applied emission factors. For the sources represented by an * in the table, discharges are estimated using Environmental Release Categories (ERCs) under REACH which are worst case estimate used for Tier 1 (initial) risk estimates. For apparel, however, available data indicates that the applied ERCs rather represent realistic emissions and the emission factor may even be higher (see section 2.2.1). A comparison on these estimates and the estimated content of the sewage based on measurements is provided in section 6.2.

Table 91. Potential sources of PFASs in sewage in 2021

Sources	Potential discharge, kg/year			Uncertainty rating
	PFAAs and other PFAS	TFA related PFAS	Polymeric PFAS	
Apparel	2,730	0	1,339	Medium
Textiles, upholstery, leather, and carpets *	960	0	874	Large
Food contact materials and packaging *	25	0	115	Large
Metals plating/metal products *	68	0	1,700	Large
Consumer mixtures *	380	0	-	Large
Cosmetics *	400	0	-	Large
Medical devices *	2,400	0	1,000	Large
Transport sector *	114	0	2,275	Large
Electronics & manufacture of semi-conductors	0	0	40	Large
Energy sector *	270	0	85	Large
Construction materials/products *	970	0	7,450	Large
Lubrication *	4	0	1,120	Large
Firefighting foams	388	0	-	Large
Pesticides	0	64	0	Medium
Pharmaceuticals	0	6175	0	Medium
Human excretions (excl. pharmaceuticals) ***	0.22	n.d.	n.d.	Medium
Solid waste pretreatment	10	negl.	n.d	Medium
Leachate from landfills	13.2	10.6	Negl	Medium
Wastewater from incinerators	0.04	?	Negl	Medium
Rainwater	37.2	654	n.d.	Medium
Total (rounded)	8,800	6,900	16,000	

* Estimated using Environmental Release Categories (ERCs) under REACH, which are worst case estimate used for Tier 1 (initial) risk estimates. For apparel however, available data indicates that the applied ERCs rather represent realistic emissions and the emission factor may even be higher.

** The PFAS restriction proposal does not distinguish between life cycle phases; however, from the overall description of uses, the main releases would occur from the production of the devices and not from their use in the health sector. It is highly uncertain as to whether these processes take place in Denmark

***Estimated on the basis of a daily intake of ∑12 PFAS with food of 103 ng/day in Norway (Haug et al, 2010)

n.d.: No data. Negl.: No data but considered negligible.

4.2.2 The distribution of discharges from the sewerage systems

The distribution of discharges from the sewerage systems in Denmark is shown in Table 92 below.

For calculations for total discharges of PFASs to surface waters, it was assumed that the PFAS concentration in stormwater overflow from combined sewer systems is similar to the concentration of PFASs in the influent to sewage treatment plants. For the surface run-off discharged into separated sewers, it was assumed that the PFASs in the water discharged to surface water are similar to the concentration in the runoff. Some PFASs may be accumulated in sedimentation basins in the separated sewer systems, but the fate of the sedimented PFASs is unclear and such accumulation has not been taken into account.

Table 92. Distribution of discharges from separate and mixed sewerage systems in 2021 (Danish EPA, 2023d)

Type of discharge	Volumes Million m^3	Percent of total
Discharge of treated water from sewage treatment plants	646.1	67%
Surface run-off (from separate sewers)	279.2	29%
Overflow from combined sewerage systems	34.4	4%
Total	959.7	100%

4.2.3 Measured concentrations of PFASs in influent, effluent and sewage sludge

Measured PFASs in influent and effluent from Danish STPs

Average concentrations of measured PFASs in the influent and effluent of Danish sewage treatment plants are summarised in Table 94 and the average concentrations of each individual PFAS are summarised in Table 93.

The dataset used to determine the influent and effluent of PFAS concentration in Danish treatment plants are taken from the Danish environmental portal PULS and consist of PFAS analysis from a selection of 36 MBNDK[27] treatment plants (treating roughly 50% of the Danish wastewater) selected by the Danish EPA to be used to represent the average concentration from all 289 MBNDK treatment plants in Denmark. This selection came from another project estimating the cost of PFAS treatment at the wastewater treatment plants. The 289 MBNDK treatment plants in Denmark treat 96% of the total wastewater produced. All analyses were performed between 2020 and 2023. The analysis package primarily used for PFAS detection at the Danish sewage treatment plants is the ∑16 PFAS package, which was formerly the common choice at sewage treatment plants. Today it is more common to measure the $PFAS_{22}$ concentration.

The dataset consisted of 537 analyses for the influent and 785 analyses for the effluent. Measurements below the detection limit (LOD) were calculated as being half the detection limit, except in cases where the detection limit was above 50 ng/L; these results were disregarded. The dataset consisted of data for 36 sewage treatment plants, but for many of the plants, the quantification limit used was so high that the concentrations for most substances were above

[27] MBNDK: Danish abbreviation for plants treating the sewage mechanically, biologically (under anaerobic, aerobic and denitrifying conditions) and chemically.

the detection limit, or the dataset included only measurements for a few PFASs. Consequently, the dataset with useful data was reduced to 14 plants for influents and 20 for effluents. The 14 plants with both influent and effluent data represented a total sewage volume of 188 million m³, corresponding to approximately 29% of the total volume of sewage treated in Danish STPs. From one STP, an outlier value for one substance that was 10-100 times higher than other values measured in the same STP was removed.

As shown in Table 93, the individual PFAS with the highest reported concentrations in the influent is PFPeA with an average concentration of 8.2 ng/L, and in the effluent, it is PFHxA with an average concentration of 6.6 ng/L. Due to the low number of STPs and high variation, differences between influent and effluent for individual substances cannot be considered significant.

Table 93. PFAAs and precursors in influent and effluent from 14 sewage treatment plants in Denmark in 2021 (Danish EPA, 2023g)

	Chain length	Avg. influent concentration ng/L	Range	Avg. effluent concentration ng/L	Range
PFBS	C4	1.9	0.6 - 9.2	3.8	0.5 - 41
PFBA	C4	3.5	1.1 - 10.4	5.6	0.5 - 60.5
PFPeS	C5	0.7	0.2 – 5.0	0.5	0.2 – 5.0
PFPeA	C5	8.2	0.7 - 28.4	4.3	1.4 - 18.5
PFHxS	C6	1.7	0.2 – 5.0	0.8	0.2 - 1.7
PFHxA	C6	2.8	0.7 - 6.8	6.6	2.1 - 23.5
PFHpS	C7	0.6	0.2 – 5.0	1.1	0.2 – 5.0
PFHpA	C7	1.2	0.5 - 2.3	1.7	0.5 – 4.0
PFOS	C8	2.5	1.2 - 6.4	3.0	0.5 – 21.0
PFOA	C8	3.1	1.1 - 4.9	4.5	2 - 14.9
PFNA	C9	0.5	0.2 - 1.6	0.7	0.2 – 4.0
PFDS	C10	0.7	0.2 – 5.0	1.0	0.2 - 50
PFDA	C10	0.6	0.2 - 1.6	0.7	0.2 - 2.8
PFUnDA	C11	0.7	0.2 – 5.0	1.0	0.2 – 5.0
PFDoDA	C12	0.7	0.2 – 5.0	1.0	0.2 – 5.0
PFTrDA	C13	1.0	0.5 – 5.0	1.3	0.5 – 5.0

The average concentrations of the ∑16 PFASs and $PFAS_4$ are shown in Table 94. The range shown represents the difference between the minimum and maximum of individual measurements.

All the plants are of the MBNDK type (mechanical, biological, nitrification, denitrification and chemical), which is used for treatment of approximately 96% of the sewage in Denmark. The 36 plants are considered representative for the sewage treatment of Danish STPs. Concentrations of PFASs in sludge are measured separately from influents and effluents; as such, it is not possible to establish a mass balance for the STPs.

Even though some of the PFASs end up in sewage sludge, the measured concentration in the effluent is higher than the concentration in the influent, indicating the formation of the measured PFASs from precursors in the incoming sewage.

Table 94. Average concentrations of measured PFASs in influent and effluent of Danish sewage treatment plants, 2020-2023 (Danish EPA, 2023g)

Measured substances	Influent concentrations, ng/L			Effluent concentrations, ng/L		
	Mean value	Range *	Number of plants	Mean value	Range *	Number of plants
∑16 PFAS	30.4	11 - 63	14	37.5	15 - 192	20
$PFAS_4$	7.8	3.4 - 13	14	8.9	3.9 - 41	20

* Range of mean values for the various sewage treatment plants.

Data from PULS included 75 other point sources with direct discharges to surface water. Of the 75 point sources, data on PFASs in the discharges were available for 18 point sources. The data are shown in Appendix 5.

Another dataset is reported in an unpublished note by Technological Institute (2023a) for the Danish EPA. The dataset includes measurements of $PFAS_{22}$ in influents from 58 STPs and effluents from 80 STPs (with a complete dataset for 49 STPs). Average concentrations were not reported in the note, but in a parallel study on PFASs in sewage sludge (Technological Institute, 2023b), the average $PFAS_{22}$ concentrations in influent and effluent were reported to be 9 and 36 ng/L, respectively. Compared with the data presented in Table 94, the input concentrations are remarkably low, whereas the concentrations in the effluent are similar. For plants where both inlet and outlet had been analyzed for all 22 PFASs, the degree of reduction through the plant was calculated. The authors concluded that neither STP size nor type (with or without chemical phosphorus precipitation) had a significant effect on the degree of reduction of PFASs as influent passes through a plant. On the other hand, chemical characteristics such as types of PFASs and chain length were shown to significantly influence the degree of reduction through the plant.

PFAS pharmaceuticals. A study of pharmaceuticals in influents to sewage treatment plants in Denmark included analyses of two pharmaceuticals with a $-CF_3$ moiety: Bicalutamide and Fulvestrant (COWI, 2021). The concentration of Fulvestrant was below the detection limits in 14 measurements from 4 plants, which ranged from 20 to 500 ng/L. For Bicalutamide, the measured concentrations ranged from 10 to 540 ng/L, with an average concentration of 148 ng/L (average not reported but estimated by COWI from original data). The concentration of Bicalutamide was about three times the ∑16 PFAS concentration reported in Table 94, demonstrating that PFAS pharmaceuticals may contribute significantly to the total PFAS concentration in wastewater in Denmark, as also demonstrated in Sweden (further described below). No data were available for other PFAS pharmaceuticals in sewage in Denmark. In Sweden, Bicalutamide was demonstrated to account for 3.5% of extractable organic fluorine in the sludge from a STP, about twice the concentration of ∑16 target PFAS. The 16 PFASs are not exactly the same as the 16 PFASs measured in Danish STPs shown above (Spaan et al., 2023a).

Polymeric PFASs. No investigations on polymeric PFAS, e.g., in the form of PTFE microplastics in sewage and sludge have been identified from Denmark or from the literature. Studies demonstrating that PTFE microplastics are released from cookware have been published (Luo et al., 2022), but no assessment of potential quantities released to wastewater are available. From the available data it cannot be assumed that the amounts are negligible, and the estimates are consequently assigned n.d.

PFASs in sludge

Average concentrations of measured $PFAS_{22}$ and $PFAS_4$ in sewage sludge from Danish sewage treatment plants are shown in Table 95. Danish EPA (2023c) does not report on the concentrations of the individual PFASs in the sludge.

Jensen et al. (2023) report on median concentrations of 22 PFASs in 215 sludge samples, but do not report average concentrations. The highest median concentrations are reported for PFOS (4.5 µg/kg) and PFDA (2.4 µg/kg).

Table 95. Average concentrations of measured PFASs in sewage sludge in 2021 (Danish EPA, 2023c)

Measured substances	Concentration in sludge, µg/kg		Number of reports
	Mean value	25 - 75 percentile *	
$PFAS_{22}$	15.3	7.6 - 18.0	346
$PFAS_4$	10.0	4.1 - 12.0	374

* Percentile of reports (data on range of mean values from sewage treatment plants not available)

4.2.4 Literature review of PFASs in sewage and sludge

Available data shows that the target PFASs (in this case $PFAS_4$, $PFAS_{22}$, and ∑16 PFASs) only account for a small fraction of the total PFASs in the sewage and the sewage sludge. In order to estimate the likely content of total PFASs in the sewage and sludge, with the aim of comparing the total content of PFASs in the influent to the listed sources of PFAS, a review of the identified literature is presented below. The description concerns total extractable organic fluorine (EOF) and the presence of side-chain fluorinated polymers and other polymers, monomeric precursors of PFAAs as well as active substances with $-CF_3$ moieties in and pharmaceuticals, plant protection products, and biocidal products.

No data on EOF vs. target PFASs from Danish investigations have been identified.

Target PFASs and extractable organic fluorine (EOF)

Studies comparing total concentration of the target (specifically measured) PFASs with total extractable organic fluorine (EOF) indicate that the target PFASs only account for a small proportion of the total PFAS content in influent sewage, effluents and sewage sludge. None of the studies include actual mass balances of PFASs in influent, effluent and sludge that would demonstrate the fate of the target PFASs and EOF in the plants.

Nordic investigation of EOF vs. target PFAS. Kärrman et al. (2019) analysed a total of 99 PFASs and total extractable organic fluorine (EOF) in samples of effluents from sewage treatment plant and sewage sludge from the Nordic Countries (same data presented in Aro et al. 2021). The results indicate a major difference between the sewage water and sludge as to the contribution of target PFASs to the total PFAS content. This is of importance for the concentrations estimated in the current study and consequently, the results are described in detail. The study showed that the sum of the 99 measured PFASs could explain, on average, 9% (range 2-21%) of the measured EOF for sewage sludge and 11% (2-17%) of the EOF in effluents from the sewage treatment plants. The study does not indicate what could be the sources of the remaining EOF. The average ∑99 PFAS concentration in effluent from the two analysed Danish sewage treatment plants was 52.3 ng/L (50.1 and 54.4 ng/L). The concentration was about 50% higher than the average ∑16 PFAS concentration from Danish sewage treatment plants reported in Table 94. The ultra-short-chain PFASs accounted for 6% of the total PFAS concentration in the samples from Finland, Sweden, Denmark, Norway and the Faroe Islands. The total concentrations of ∑99 PFAS in sludge samples from two Danish sewage treatment plants were 141.9 µg/kg (135.3-148.4), about 10 times the concentrations og $PFAS_{22}$ reported

in Table 95, but lower than the concentrations reported by Fredriksson et al. (2020). The homologue profiles of the sludge samples were dominated by PFCA precursors, on average accounting for 75.0% of all identified PFASs. This was mainly driven by 6:2 diPAP, 8:2 diPAP, 6:2/8:2 diPAP, 6:2/10:2 diPAP and 6:2/12:2 di-PAP, which were present in all samples. Di-PAPs are commonly used during paper production, and they are extensively utilized in the impregnation of paper and cardboard products. None of these substances are included in $PFAS_{22}$. The second largest contributors were PFSA precursors with 14.0% of all identified PFASs. MeFOSAA and EtFOSAA accounted for about 90.0% of all PFSA precursors. None of these substances are included in $PFAS_{22}$. In total, PFCAs and PFSAs accounted for about 10% of the measured ∑99 PFAS and the total concentration of PFCAs and PFCSs (approximately 15 µg/kg) were close to the concentrations reported in Table 95. The ∑99 PFAS concentrations were relatively high in the Danish sludge samples as compared to neighbouring countries, but the percentage represented by the PFAAs was not dissimilar from the average across the countries.

Swedish study of EOF vs. target PFASs in sludge and the contribution from pharmaceuticals. A recent study by Spaan et al. (2023a) indicates that pharmaceuticals account for a significant proportion of the extractable organic fluorine in municipal sewage sludge from Stockholm, Sweden. The results indicated that approximately 27% of the EOF was attributed to the analysed "conventional" monomeric PFASs (23 PFASs), pharmaceuticals and pesticide substances. The analysed fluoropharmaceuticals and metabolites accounted for 22% of the EOF. PFAS pharmaceuticals (with at least one $-CF_3$) alone accounted for 10.4% of the EOF. The PFAS pharmaceutical with the highest concentration was Bicalutamide, which accounted for 3.5% of the total EOF with a concentration around 65 µg/kg d.w. The total concentration of PFAS pharmaceuticals is not reported, but the 10.4% of the EOF corresponds approximately to a concentration of 193 µg/kg d.w. The measured fluoropesticides accounted for 0.3% of EOF. The sum of 16 target monomeric PFAAs accounted for 1.4% of EOF (average concentration of 12.5 µg/kg d.w), whereas an additional 7 monomeric PFAA precursors[28] (all substances not included in the $PFAS_{22}$ used for monitoring in Denmark) accounted for 3.7%. Compared with the results of Kärrman et al. (2019), where the concentration of precursors were 10 times the concentration of sum of target PFAAs, the concentration of precursors is only three times the concentration of the conventional target PFAS in the study of Spaan et al. (2023). Spaan et al. (2023) note that the concentration and contribution of diPAPs were significantly lower than reported in a previous Swedish study. The mean value of 12.5 µg/kg d.w. for ∑16 PFAAs reported by Spaan et al. (2023) is close to the average $PFAS_{22}$ concentration of 15.3 µg/kg d.w. reported for Danish sewage sludge (Table 95), whereas the total ∑22 target PFASs was approximately three times this. The authors suggest that the sources of the remaining unidentified organofluorine is unclear, but may include additional pharmaceuticals, pesticides and transformation products of pharmaceuticals not captured by the study. Furthermore, neutral PFAS, such as perfluoroalkyl sulfonamides, fluorotelomer alcohols, silicones, and olefins, are known to occur in consumer products and may also contribute (Spaan et al., 2023).

Preliminary results of EOF vs. target PFASs in sewage. Preliminary results from the same research group, presented at a conference in 2023, indicate that the ∑19 target PFASs accounted for approximately 1% of EOF in both influent and effluent from a sewage treatment plant in Örebro, Sweden (Larsson et al., 2023). The preliminary results indicate that ultra-short-chain PFASs (three substances) accounted for about 7% of EOF in influent and 4% in effluent, similar to the results of Kärrman et al. (2019). ∑15 fluoropharmaceuticals and

[28] Seven additional PFAS: 5:3 FTCA, 6:2 diPAP, EtFOSAA, MeFOSAA, H-PFOS, 8:2 diPAP, and 6:2/8:2 diPAP.

metabolites accounted for about 12% in both influent and effluent (not indicated whether all fluoropharmaceuticals fall under the definition of PFAS).

Austrian study on EOF vs. target PFASs in sewage. In a recent study from Austria, Müller et al. (2023) found that the ∑31 target PFASs increased from 22-47 ng/L in the influent to 140-213 ng/L in effluent, while the concentration was measured at 10 µg/kg in sludge. EOF was found to be approximately the same (2,300 - 3.500 µg F/L) in influent and effluent, whereas it was 280 µg F/kg in the sludge. Mass balance analysis showed an increase in the identified PFAS compounds in the effluent compared to the influent, suggesting biotransformation of non-targeted PFAS precursor compounds. The study does not provide data on water flow and mass of sludge generated and does not set up the mass balance for EOF or target PFAS.

German assessment of pharmaceuticals and sources of TFA. A German assessment of sources of TFA undertaken for Umweltbundesamt (2021) estimates that the PFAS pharmaceuticals used in Germany in 2020, if it is assumed that they are 100% degraded to TFA (which the assessment indicates as unrealistic), could release a maximum of about 29 t/a of TFA (tonnage of PFAS pharmaceuticals not indicated). Of this, 23% may derive from anesthetic gases emitted to the atmosphere. For the remaining 71% (20 t/y), it is assumed that the pharmaceuticals and their degradation products are transported from toilets to sewage treatment plants and from their effluent into surface waters, where they tend to degrade rather slowly. Small amounts may be spread in sludge on agricultural land. While there are indications suggesting that a small proportion of TFA may be formed from human pharmaceuticals in sewage treatment plants, Umweltbundesamt (2021) assumes that the bulk of human pharmaceuticals are introduced unchanged into surface water. The assessment does not provide actual concentrations in effluent and sludge or distribution factors. In the current study, the releases of PFAS pharmaceuticals to wastewater is estimated at 6.1 t/y (not TFA equivalent) which is well in accordance with the German data on a *per capita* basis.

According to Scheurer et al. (2017), TFA was neither removed by biological sewage treatment, nor by a retention soil filter used for the treatment of combined sewer overflows. WWTP influents can even bear a TFA formation potential when appropriate CF_3-containing precursors are present. According to the authors, biological degradation and ozonation batch experiments with chemicals of different classes, including various PFAS pesticides and 4:2 fluorotelomer sulfonate, proved that there are yet overlooked sources and pathways of TFA which need to be addressed in the future.

Side-chain fluorinated polymers and other polymers

Side-chain fluorinated polymers in sewage sludge in Sweden. In a pilot study of the side-chain fluorinated polymer ingredients of Scotchgard™ products from 3M (described in section **Error! Reference source not found.**) and their levels in STP sludge and landfill leachate from Sweden, Fredriksson et al. (2020) found detectable levels of pre-2002 products (where PFOS was still used) and post-2002 products (with shorter chain PFAS) in all 14 analysed sludge samples at levels of 150-2,618 µg/kg d.w. Levels of pre-2002 products were always higher than those of post-2002 in the same samples. No relationship between number of people that the wastewater treatment plants served and the concentrations of EOF and pre-2002 and post-2002 products could be observed. The concentrations of pre-2002 and post-2002 products in sludge were three times higher than the ∑93 PFAS analysed in a previous screening study by the same authors. The average concentration of Scotchgard products was 875 µg/kg, as compared to the average concentration of ∑93 PFAS, reported to be 295 µg/kg. From one STP, measurements of pre-2002 products in historic samples were undertaken, and a decreasing trend from 2,500 µg/kg in 2004 to 500 µg/kg in 2016 was observed. The Scotchgard products and ∑93 PFAS accounted for up to 4% of the EOF. The fluorine content of the pre-2002 products was determined at 0.5-0.7%, whereas the fluorine content of post-2002 products was 1.9-2.2% (note: this is the percentage of F in the mixture and not the side-chain

fluorinated component). In the current substance flow analysis, as well as the quantitative assessment of the PFAS restriction dossier, the PFASs are represented by the total weight of their substances, regardless of their fluorine content or content of perfluorinated moieties. If it is assumed than the concentrations represent the technical products and the fluorochemical urethane accounts for 2% of the technical product, the concentration of the fluorochemical urethane would still be 18 µg/kg, a higher concentration than the $PFAS_{22}$ concentration in sewage sludge in Denmark.

Canadian studies. The same two Scotchgard components were investigated in two studies in Canada, summarised in Table 96. In sewage sludge from 20 STPs in Canada, the ∑22 PFAS ranged from 4.9 to 92 µg/kg d.w. with an average of 30 µg/kg, while the total average concentration of the Scotchgard components was 926 µg/kg d.w. (range: 39 - 2,156) µg/kg d.w. (Letcher et al, 2020). Recalculated into total fluor (F) content, the difference was less pronounced, as the F-content of the ∑22 PFAS was estimated at 90% of the total weight whereas for the Scotchgard components, F-content was only 11%. Measured as total fluor (F), the ∑22 PFAS corresponded to an average F concentration of 21 µg F/kg d.w. (range 3.3 - 63 µg F/kg d.w), while the Scotchgard components corresponded to an average F concentration of 101 µg F/kg d.w (range 4 - 228 µg F/kg d.w). The contribution of the Scotchgard components to the total fluorine content of the sludge was consequently approximately five times the contribution from the ∑22 PFAS.

Application of sludge to agricultural soils has been demonstrated to result in elevated concentrations of Scotchgard components in the soil. Chu and Letcher (2017) collected thirteen soil samples from a biosolid-applied and two non-biosolid-applied farm field sites in southern Ontario, Canada. The Scotchgard components were detected in 100% of the soil samples from biosolid-augmented agricultural sites (n=3) with an average concentration of the two components of 240 µg/kg d.w. The mean ∑22 PFAS concentration in the soil samples from the same sites was 2.4 µg/kg d.w. In soils which had received no biosolids, the average concentration of the Scotchgard components was 3.2 µg/kg d.w. and the ∑22 PFAS concentration was below the detection limit (full dataset only available from one of the sites). The concentrations were not represented as total F. If the total F percentages used by Letcher et al. (2020) are applied, the average concentration of the Scotchgard components on biosolid applied soils can be estimated at 26 µg F/kg d.w., whereas the concentration of ∑22 PFAS can be estimated at 1.7 µg F/kg. Still, expressed as total F, the concentration of the Scotchgard components was 15 times higher than the concentration of ∑22 PFAS. The same study included analysis of the Scotchgard components in sediments from the Great Lakes, where the concentrations of the Scotchgard components exceeded the concentration of ∑22 PFAS.

Table 96. Side-chain fluorinated Scotchgard components and ∑22 PFAS in sewage sludge and biosolid applied farm fields in Canada

	n	Scotchgard components µg/kg d.w.	Scotchgard components µg F/kg d.w.	∑22 PFAS µg F/kg d.w	Source
Sewage sludge	20 STPs	926	101	21	Letcher et al., 2020
Biosolid applied farm fields	3 sites	240	26	1.7	Chu and Letcher, 2017

In Denmark, the Scotchgard products only represent a fraction of the side-chain fluorinated polymers used in apparel and other TULAC applications. Lassen et al. (2015) lists nine producers of different brands; among these the common Teflon® Fabric Protector from DuPont/Huntsman. It is not clear to what extent side-chain fluorinated polymers from other

manufacturers would also be analysed by the same procedures used in the studies quoted above.

C8-FASA-based copolymers in sewage sludge. Fredriksson et al. (2022) analysed C4 and C8-FASA-based copolymers in sludge from STPs in Sweden. The concentration of the C8-FASA-based copolymer, which was the highest of the two, was in the same range as all other measured PFASs together when quantified by the available technical mixture. The concentration of the C4- and C8-FASA-based copolymer (as technical mixtures) were in the ranges 21-218 and 91-2,094 µg/kg d.w., respectively, whereas the concentration of ∑79 anionic and neutral PFASs was between 50 and 1,124 µg/kg d.w. In order to compare the levels of the copolymers with the other 79 PFAS, the concentration of FASA-based copolymers was normalized to fluorinated side-chain equivalents (FSC), based on the structure and the total fluorine content of the technical mixture used for calibration (this was only done for the C8-FASA-based copolymer). The concentrations of the FASA-based copolymers in sludge were estimated by this method to be between 1.4 and 22 µg FSC-eq/kg d.w.

EOF and recovery of fluorinated polymers. As was observed in a number of studies, there appears to be a significant gap between estimated outputs from PFAS applications to wastewater and the PFAS amounts quantified by measurements of extractable organic fluorine in wastewater in Denmark. Stockholm University's Dept. for Environmental Sciences, a leading institute in measurement of PFAS, was therefore contacted on the topic. Beskin (2023) confirmed that it appears to be difficult to recover fluorinated polymers, including side-chain-fluorinated polymers, quantitatively from wastewater and sewerage sludge samples.

Emission to air from STPs

No data on emission of PFASs to air from STPs in Denmark are available.

Canadian studies. Ahrens et al. (2011) measured PFAS concentrations over a municipal STP in Canada for 69 days in 2009. The samples were analyzed for 18 PFASs in five PFAS classes to investigate their concentration in air, composition and emissions to the atmosphere. ∑18 PFAS concentrations in air were 3-15 times higher within the STP (2,280-24,040 pg/m^3) compared to reference sites (597-1,600 pg/m^3). The volatile FTOHs were the predominant PFAS class in air for all STPs with 6:2 FTOH as the dominant compound (895-12,290 pg/m^3). Furthermore, among the PFAAs PFOS was dominant in the air over the STP (43-171 pg/m^3) followed by PFBA (55-116 pg/m^3).

Highly elevated PFAS concentrations in the air were found near the aeration tanks compared to the other tanks. The authors suggest this was likely associated with increased volatilization during aeration that may be further enhanced through aqueous aerosol-mediated transport. Total yearly ∑18 PFAS emissions estimated using a simplified dispersion model were 2.6 kg/year for the STP. The *per capita* emissions for the WWTP were estimated using the emissions rates in µg per year and the population served by the WWTP (~1 million people). The authors note that this *per capita* estimation must be considered with caution because it is based on one municipal STP and does not account for possible commercial and industrial wastewater contributions. The estimated *per capita* emissions for the ∑18 PFAS from the STP to air were 2,560 µg/year/person.

Comparing the estimated emissions from the STP with literature data on total discharges from STPs in Germany and Switzerland, Ahrens et al. (2011) conclude that the discharges of PFASs to surface water from the reported plants would be 2 - 10 times higher than the calculated emissions to air.

In the only other study of air emissions from STPs identified in the literature, Shoeib et al. (2016) investigated PFAS emissions to air from several types of STPs in Canada: secondary

activated sludge in urban areas, secondary extended aeration in towns and facultative lagoons in rural areas. The concentrations of target PFASs in air were ~1.7- 35 times higher on-site compared to the corresponding off-site location. Higher air concentrations were observed on-site during summer compared to winter. At all sites, the highest concentrations were obtained for the FTOHs (6:2, 8:2 and 10:2 FTOHs) representing 61± 24% of Σ22 PFASs. Annual emissions of Σ22 PFASs to air were estimated at 10-110 g/tank, confirming that PFAS emissions to air from sewage treatment may be a significant source. The authors note that the estimated emission per tank was lower than estimated by Ahrens et al. (2011), quoted above.

Extrapolation to the Danish situation. If the above *per capita* emission is applied for the Danish population, total emission of PFAAs and precursors from Danish STPs would be approximately 15 kg/y, which is about half of the ∑16 PFAS discharges from Danish STPs (see section 4.2.5), but significantly lower if compared to the total discharges of PFAAs and precursors. The difference between the air emission extrapolated to Denmark and the estimated effluents of ∑16 PFAS from Danish SPTs are within the indicated range of 2-10 indicated by Ahrens et al. (2011).

4.2.5 Estimated input to and output from sewage treatment plants and overflows

Influent and effluent from sewage treatment plants

PFAASs and other PFASs. In total, 646.1 million m^3 sewage is treated annually at Danish sewage treatment plants**.** Based on the measured concentrations, it can be estimated that the total content of ∑16 PFAS in the influent in 2021 was around 30 kg/year, while the total $PFAS_4$ content was around 8 kg/year.

However, this represents only a small fraction of total PFASs. Very limited information is available on the concentration of the ∑16 PFAS in influent compared to the concentration of other PFASs and EOF. Significantly more information is available on the content of other PFASs in sewage sludge, and the total PFASs in sewage sludge must originate in the influent.

As described further below, the total estimated $PFAS_{22}$ content of sludge was 1.7 kg/y, which only corresponds to 10% of ∑16 PFAS in the influent to the treatment plants, which in turn indicates that more than 90% of the target PFAAs in the influent is discharged with the effluent. It is generally understood that PFAAs are not degraded within the plants. As shown, the concentration of target PFASs in effluent is higher than in the influents due to some formation from precursors, but the majority of target PFASs in sewage sludge and effluents appears to be present at the time that the sewage reaches the sewage treatment plant.

The study of Kärrman et al. (2019), showed that the sum of the 99 measured PFASs could explain 9% on average (range 2-21%) of the measured EOF for sewage sludge and 11% (2-17%) of the EOF in effluents from the sewage treatment plants. This could indicate that same differences between total PFASs demonstrated in sewage sludge (and summarized below the table) would also apply to the influent and effluent. Below, it is estimated that the total concentration of PFAAs and precursors is 17 times the concentration of ∑16 PFAS. In the absence of more data on the distribution of different PFASs in sewage, the same factor is applied in this study. However, even taking this factor into account, the total estimated content of PFAAs and precursors in the influent is lower than expected, based on the assessment of the likely sources of PFASs in sewage in Table 91.

TFA related PFASs. As described above, an average concentration of 148 ng/L was measured for the pharmaceutical Bicalutamide in Danish STPs. In a Swedish investigation, this pharmaceutical accounted for 3.5% of extractable organic fluorine in the sludge from a STP,

while all quantified PFAS pharmaceuticals and metabolites accounted for 10.1% (Spaan et al., 2023). In addition, fluoropesticides (not necessarily PFAS) accounted for 0.3%. The total quantified pharmaceuticals, metabolites and pesticides was consequently about 3 times the concentration of Bicalutamide (approx. 450 ng/L). Spaan et al. (2023) suggest that unidentified EOF may include additional pharmaceuticals and metabolites, pesticides and transformation products. In the absence of actual data and considering the estimated quantities of pharmaceuticals discharged to sewage, a value of 1000 ng/L in the influent was applied as best estimate. Consequently, the concentration in the effluent was adjusted to take into account the amount in sewage sludge. A relatively low proportion of the pharmaceuticals ending up in sewage sludge is in accordance with Umweltbundesamt (2021) which indicated that "*it must be assumed that the bulk of human pharmaceuticals is introduced unchanged into surface water*". A Danish investigation of the fate of pharmaceuticals in a sewage treatment plant found that 10 out of 25 investigated pharmaceuticals had a removal rate higher than 75%. On average, a removal rate of 63% was seen for 22 of the 25 medicinal pharmaceuticals (Aarhus Vand, 2021) It has not in this study been investigated to what extent removal rates may depend on the presence of a $-CF_3$ moiety.

Table 97. Estimated quantities of PFASs in influent and effluent from Danish sewage treatment plants

Substances	Sewage volumes million m^3	Influent		Effluent	
		Average concentration ng/L	Total quantity kg/y	Average concentration ng/L	Total quantity kg/y
∑16 PFAS	646	30.4	20	46.4	30.0
$PFAS_4$	646	7.8	5	9.1	5.9
PFAAs and precursors	646	520	336	455	294
TFA related PFASs	646	1000	646	916	592
Polymeric PFASs	646	n.d	n.d	n.d	n.d
Total quantified			982		885

n.d.: No data.

Sewage sludge

PFAAs and precursors. The estimated quantities of PFAAs and precursors disposed of in sewage sludge by disposal method is summarized in Table 98.

The average $PFAS_{22}$ concentration in the sludge of 15.3 µg/kg d.w. is close to the ∑16 PFAS concentration of 12.5 µg/kg d.w. reported by Spaan et al. (2023) to account for only about 1.4% of the total EOF in sewage sludge from a Swedish STP, while other target PFASs accounted for 3.7% of the EOF (i.e. the total target PFAS concentration was thus 46 µg/kg). The total concentrations of ∑99 PFAS in sludge samples from two Danish sewage treatment plants were 141.9 µg/kg (Kärrman et al., 2019), i.e., more than 10 times the average $PFAS_{22}$ concentration. In addition to the contribution from the non-polymeric precursors, there is a contribution from side-chain fluorinated polymers: for just one of the known side-chain fluorinated polymers, the Scotchgard products, the concentration of fluorochemical urethane (the active side-chain fluorinated polymer of the Scotchgard surface protector) was estimated at approximately 18 µg/kg. Considering that a number of side-chain fluorinated polymers are used, the contribution from side-chain fluorinated polymers would likely be on the order of 100 µg/kg (considered

part of PFAAs and precursors in this study). On this basis, as a best estimate, the total concentration of PFAAs and precursors is assumed to be 250 µg/kg. The study of Letcher et al. (2020) found that the average concentration of the Scotchgard products in sewage sludge was 30 times the concentration of ∑22 PFAS. This may indicate that the total PFAS concentration in the sewage sludge may be even higher than estimated here.

Table 98. Disposal of PFAAs and precursors with sewage sludge in 2021 (Danish EPA, 2023c)

Disposal type		$PFAS_{22}$		$PFAS_4$		Total PFAAs and precursors	
	Quantity sludge t d.w./y	Concentration µg/kg d.w.	Quantity kg/y	Concentration µg/kg d.w.	Quantity kg/y	Concentration µg/kg d.w.	Quantity kg/y
Use on agricultural soil	83,000	15.3	1.3	10.0	0.8	250	20.8
Compost and other use	16,000	15.3	0.2	10.0	0.2	250	4.0
Incineration	10,000	15.3	0.2	10.0	0.1	250	2.5
Total	109,000	15.3	1.7	10.0	1.1	250	27.3

TFA related PFASs. The estimated quantities of TFA related PFASs and polymeric PFASs disposed of as sewage sludge by disposal method is summarized in Table 99.

For the TFA related PFASs, the PFAS pharmaceuticals were considered to account for the majority. Spaan et al. (2023a) measured PFAS pharmaceuticals and metabolites at a total concentration of 193 µg/kg d.w. but notes that the unidentified EOF may include additional pharmaceuticals and metabolites, pesticides and transformation products. Considering the large quantities of PFAS pharmaceuticals expected to be discharged to the sewage system, it is likely that the concentration of the TFA related PFASs is well above 193 µg/kg d.w. Therefore, a best estimate of 500 µg/kg d.w. will be applied in this study.

Polymeric PFAS: No data are available for quantification of the polymeric PFASs in sewage.

Table 99. Potential disposal of TFA related PFASs and polymeric PFASs in sewage sludge in 2021

Disposal type	Quantity sludge t d.w./y	TFA related PFASs		Polymeric PFASs
		Concentration µg/kg d.w.	Quantity kg/y	Quantity, kg/y
Use on agricultural soil	83,000	500	41.5	n.d.
Compost and other use	16,000	500	8.0	n.d.
Incineration	10,000	500	5.0	n.d.
Total	109,000	500	54.5	n.d.

n.d.: No data.

Incineration of sewage sludge. In Denmark, in 2021, 10,000 t d.w. of sludge was burned in MSWIs or in dedicated sludge incineration plants located at the wastewater treatment plants. There are currently six plants that either use combustion in a rotary kiln, in a fluid bed reactor, or the sludge is thermally decomposed by pyrolysis (Geertinger et al., 2023). Geertinger et al. (2023) include a review of various techniques for thermal treatment of sludge and their ability

to destruct PFASs, but do not summarise the fate of PFASs by thermal decomposition of sewage sludge.

In a test of incineration of two types of sludge in a fluid bed incinerator for sewage sludge incineration, BIOFOS did not detect PFASs in the flue gas or fly ash above the LOQ [29]. The available data do not indicate that the releases per tonne input of PFASs should be higher from sewage sludge incineration than from MSWIs. In the absence of specific distribution factors for the incineration of sewage sludge, the distribution factors established for MSWIs in section 4.1.3 were applied. The releases of PFASs from the incineration of sludge, estimated using this method, are expected to be negligible. A similar situation is seen in comparing total PFASs in sewage sludge for incineration and total PFASs in municipal solid waste for incineration. Whereas the sewage sludge is estimated to contain a total of 13 kg of PFAS, the total PFAS content of municipal solid waste for incineration is estimated at 1,272 t/y.

The efficiency of pyrolysis in destruction of PFASs in sewage sludge has been tested in a Danish pyrolysis plant. The data are unpublished, but according to the test laboratory at Force Technology, the measurements indicated that the PFASs present in the sewage sludge could not be recovered in neither biochar nor flue gas (Force, 2024). The authors concluded that the pyrolysis resulted in total destruction of the target PFASs, but notes that short-chain degradation products with fewer than four carbon atoms were not analyzed.

Overflows

Approximately 4% of the input to the sewer system in 2021 was discharged as overflow from combined sewerage systems, while 67% was directed to STPs. As the overflow occurs during heavy rainfall incidents, the sewage is diluted with rainwater and the concentration of most contaminants is lower than the general average in influent to sewage treatment plants.

A report on typical concentrations for environmentally hazardous substances in rainfall-related discharges (Kjær and Rasmussen, 2022) reviewed the literature regarding PFASs in rainwater-determined overflow from combined sewer systems and rainwater determined discharges from separate sewer systems. For rainwater-determined overflow from combined sewer systems, typical concentrations in overflow were determined for 6 individual PFASs (PFBA, PFDA, PFHxA, PFNA, PFOS, PFOS). The typical ∑6 PFAS is 9.5 ng/L. For five of the substances (excl. PFNA), data on concentration in influents to sewage treatment plants is included in Table 93. For these five substances, the typical ∑5 PFAS is 8.7 ng/L as compared to 14.8 ng/L for the average influent concentrations for these substances summarized in Table 93.

The total PFAS concentrations in the overflows are calculated on the basis of the estimated concentration in influents and the ratio of 8.7/ 14.8 is determined for the 5 PFASs.

Total balance for sewage treatment

The total balance of PFASs in sewage management in Denmark in 2021 is shown in Table 100.

[29] BIOFOS: Forbrændingsvarme kan – måske – gøre kål på PFAS. https://mypresswire.com/dk/pressroom/39950/pressrelease/113141

Table 100. Total balance of PFASs in sewage treatment in Denmark in 2021

Flow	Input and output flows, kg/y		
	PFAAs and precursors	TFA related PFAS	Polymeric PFAS
Input to sewage treatment systems based on source estimates*	8,800	6,900	16,000
Input to sewage treatment systems based on content estimates**	350	737	n.d.
Discharge to surface water from overflow	11	20	n.d.
Discharge to surface water from separate sewage systems	4	71	n.d.
Discharge to surface water from sewage treatment plants	294	592	n.d.
Emission to air from sewage treatment plants	15	-	n.d.
Release to soil with sewage sludge	25	50	n.d.
Emission to air from sewage sludge incineration	0.000001	0.000002	n.d.
To landfill with sewage sludge incineration residues, DK	0.000006	0.000012	n.d.
Destruction by sewage sludge incineration	2	5	n.d.

* Based on source estimates in Table 91.
** The quantities are best estimates on the basis of the estimated total content of influents. The totals calculated on the basis of the source estimates is significantly higher.
n.d.: No data. Negl.: No data but considered negligible.

4.2.6 Surface run-off (separate sewers)

As mentioned in previous section, Kjær and Rasmussen (2022) reviewed the literature regarding PFASs in rainwater-determined overflow from combined sewer systems and rainwater-determined discharges from separate sewer systems. For discharges from the separate sewer systems, no typical values are reported. Ranges of PFBA, PFOA and PFOS were reported from two literature sources, but no average values were reported. In the absence of reported $PFAS_{22}$ and $PFAS_4$ concentrations, the data from the report were not taken into consideration in this study.

Pedersen et al. (2023) report on $PFAS_{22}$ and $PFAS_4$ concentrations in rainwater-determined discharges in separate sewer systems from the catchment area to Odense Å. In three measuring points in separate sewer systems, $PFAS_4$ ranged from 0.88 to 2.9 ng/L while $PFAS_{22}$ ranged from 3.7 to 12 ng/L with an average of 5.5 ng/L. The concentrations are in accordance with concentrations measured in rainwater in different countries as summarized in Table 101, but slightly lower than the 7.3 ng/L used for estimation of the atmospheric deposition in Denmark. TFA was measured at 140 to 560 ng/L with an average of 325 ng/L, in accordance with the precipitation weighted average measured in Germany (Freeling et al., 2022) that is used for estimation of the atmospheric deposition of TFA. The comparison among the concentrations in rainwater clearly indicates that rainwater may be expected to be the main source of the non-polymeric PFASs in the urban run-off in the separate sewer systems.

Other fractions may originate from dust released from apparel, coated surfaces, surface treated buildings, masonry, vehicles, etc.; it cannot be ruled out that urban run-off from larger cities would be significantly higher in PFASs than reported above. No Danish data on urban runoff from larger cities have been identified. In a larger Canadian city, the average concentration of ∑26 PFASs in stormwater was 9.0 ng/L; the authors note that the results are consistent with concentrations observed in other Canadian cities with ranges of 6.5- 16 ng/L (Codling et al., 2020). However, these measurements do not include side-chain fluorinated polymers,

which are expected to make up the majority of PFASs released to sewage and surface water based on the used quantities and emission factors.

It is assumed that the majority of the non-polymeric PFASs in the surface run-off originates from atmospheric deposition and, in the absence of other data, the content of the run-off is estimated on the basis of the estimated atmospheric deposition in Chapter 5. The contribution of side-chain fluorinated polymers have in the absence of data not been estimated, but the quantities of PFAS in the form of side-chain fluorinated polymers e.g. from apparel may quite well be significantly higher than the total for the target PFASs.

5. Atmospheric deposition

5.1 Wet and dry deposition of PFASs

Limited data are available regarding atmospheric deposition of PFASs in Denmark.

5.1.1 PFAAs and precursors

Bossi and Ellermann (2023) from the Danish Centre for Environment and Energy have recently reviewed data on PFASs in the atmosphere and deposition of PFASs. Most of the data published in the literature are obtained by sampling wet deposition. A few studies have investigated the contribution of wet and dry deposition compared to the total deposition of PFAS. The main conclusion from these studies is that wet deposition removes PFASs from the atmosphere an order of magnitude more effectively than dry deposition (Shimizu et al., 2021 and quoted by Bossi and Ellermann, 2023). PFAS concentrations found in precipitation from selected studies are summarized in Table 101.

Table 101. Summary of literature for PFAS concentrations in precipitation (from Bossi and Ellermann, 2023)

Country (no of locations)	Locations	Sampling	Number of PFASs analyzed (most frequently found)	Total PFAS min-max conc. ng/L	Sampling period	Reference
USA (8)	Wisconsin, rural	Wet only	34 (22)	0.7-6.1	April-November 2020	Pfotenhauer et al., 2022
China (1)	Chongqing, urban	Wet only	17 (13)	0.9-191.3	July 2020-April 2021	Wang et al., 2022
USA (6)	Ohio-Indiana, rural/urban	Wet only	15* (10)	50-850**	Summer 2019	Pike et al., 2021
Canada (3)	Great Lakes, urban/rural/remote	Wet only	12 (10)	0.26-14.0	2006-2018	Gewurtz et al., 2019
Sweden (1)	Råö, Remote	Bulk	16 (8)	2.18-5.88	2015	Johansson et al., 2018
Sweden (1)	Stockholm, Urban	Bulk	16 (8)	0.95-6.39	2015-2016	Johansson et al.,2018
Sweden (1)	Krycklan, Remote	Bulk	10 (9)	0.90-3.62	May-November 2011	Filipovic et al., 2015
Germany (1)	Barsbüttel - semi rural	Bulk with Filter	37 (17)	1.6-48.6	2007-2008	Dreyer et al., 2010
Denmark (7) *	Rural	Bulk	7 (4)	1.6-38.3	October 2004	Strand et al., 2007

* TFA contribution ~ 90% of total PFAS

Danish measurements. Strand et al. (2007) analysed rainwater samples for seven long-chain PFASs (PFHxS, PFOS, PFOSA, PFOA, PFNA, PFDA, and PFUnA) in seven rural locations in Denmark. The rainwater was sampled over a period of 14 days in 2004 (one sample from each location) at seven background stations for the National Monitoring Programme, NOVANA. The detection limit varied by substance from 0.2 to 3.3 ng/L. PFOS was measured in concentrations above the detected limit in samples from two locations, in concentrations of 2.4 and 1.6 ng/L. PFDA and PFUnA were measured in samples from two other locations; PFDA at 12.5 and 13.6 ng/L, and PFUnA at 13.6 and 15.1 ng/L. PFHxS was measured in one sample from one location at 0.3 ng/L. The highest concentration for the sum of the seven PFASs from one location was 38.3 g/L (43.1 g/L if measurements below the detection level are set at the detection level). The authors noted that it was possible that some contamination of the samples took place during sampling and analysis.

In 2022, the Danish television company TV2 had five rainwater samples from 5 locations in Denmark (one from each location) analysed for $PFAS_4$ (PFOA, PFNA PFHxS, and PFOS). The $PFAS_4$ concentration was below the detection limit in the sample from one location, and ranged from 0.56 to 1.5 ng/L in the other locations.[30]

Review of data on deposition in other counties

In the absence of more a comprehensive dataset from Denmark, precipitation data from other countries were reviewed.

Deposition of PFAAs in Northern Germany. Dreyer et al. (2010) analysed 20 precipitation samples taken concurrently with air samples at a semi rural Northern Germany monitoring site over a period of 7 months in 2007 and 2008. In total, 34 PFASs were determined to be in the rainwater samples. Eleven of the PFASs (PFBS, PFOS, PFBA, PFHxA, PFHpA, PFOA, PFNA, PFDA, PFDoDA, MeFOSE, MeFBSE) were detected in more than 50% of the samples. The total PFAS concentration varied between 1.6 ng/L and 48.6 ng ng/L. PFOA and PFBA were usually observed in the highest concentrations (1.8 and 2.5 ng/L on average, 9.3 and 9.4 ng/L at maximum). The PFOS concentration was around 1 ng/L. On average, the three compounds PFOA, PFBA and PFOS accounted for 60% of the determined PFAS. The average of the total concentration was not reported, but from the information above it was estimated at approximately 8.8 ng/L. The annual deposition was not reported.

Deposition of volatile PFASs in Japan. The study of Dreyer et al. (2010) did not include the volatile polyfluorinated telomers, FTOHs. In a study from Japan, Mahmoud et al. (2009) analysed FTOHs in precipitation and surface water in an urban area of Japan. The average concentrations of 8:2 FTOH, 10:2 FTOH and 8:2 FTOAcr of the precipitation samples were 1.97, 0.82 and 0.21 ng/L, respectively. The total of the three PFASs was 3.0 ng/L. The results indicated that PFASs apart from the 34 PFASs monitored by Dreyer may contribute significantly to the total.

Data from the USA. In a follow-up study from the USA, Kim et al. (2022) screened for emerging PFASs in precipitation samples from seven sites in the USA and compared the results with concentrations of the 9 PFASs conventionally monitored in the USA. Several emerging PFASs were detected across all samples, with the most prevalent compounds being C3-C8 hydrogen-substituted perfluorocarboxylic acids (H-PFCAs) and fluorotelomer carboxylic acids (FTCAs). Concentrations of emerging PFASs were in the 10-1000 ng/L range and were approximately 1-2 orders of magnitude greater than conventionally monitored PFASs at all sites. The results indicated that the conventional measurement of PFAAs and precursors in precipitation may only represent a small fraction of the total PFAS concentrations (excl. TFA).

In 2020, Pfotenhauer et al. (2022) measured a suite of 34 PFAS compounds (TFA not included) in 91 rain samples from sites across Wisconsin, USA. PFCAs were detected most frequently and constituted an average of 83% of the total mass quantified across the samples. Summed PFAS mass concentrations in the rainwater ranged from 0.7 to 6.1 ng/L with a median of 1.5 ng/L (mean value not reported). The annual average flux at the 8 sites ranged from 1.99 to 4.23 $\mu g/m^3/y$. The mean value across the 8 sites was estimated at 2.7 $\mu g/m^3/y$.

Deposition of sea foam and aerosols along the coastline

In recent years, it has been demonstrated that PFASs are being concentrated in sea foam and the surface layer of the sea and may be spread to soil and groundwater in coastal areas through aerosols and foams generated in sea water.

[30] https://nyheder.tv2.dk/samfund/2022-11-21-myndigheder-har-i-aarevis-vidst-at-det-regner-med-pfas-i-danmark-uden-at-handle

The concentration of $PFAS_4$ in sea foam samples from eight localities along the west coast of Jutland in August 2023 varied between 17,000 and 250,000 ng/L. The concentration in small seawater pools formed on the beach from the same localities varied from 3.1 to 120 ng/L, illustrating significant upconcentration of PFASs in the foam.

In 2023, the Danish Nature Agency and the Danish EPA measured concentrations of surface water and grass at 60 coastal locations (within one km from the sea) around Denmark (Danish Nature Agency, 2023). Concentrations of PFASs above the Danish Veterinary and Food Administration's indicator values were found in grass samples from 60 out of 67 locations and in water samples from 9 out of 47 locations. On the West Coast of Jutland, for all but one location, the concentration in grass samples exceeded the indicator $PFAS_{22}$ value of 0.42 µg/kg. For 23 locations by the Inner Danish Waters, 74% of the locations had grass concentrations exceeding the indicator value and some of the highest concentrations. These results illustrate that the high deposition of PFASs in sea spray in coastal zones is not limited to the west coast of Jutland.

In the current context of a substance flow analysis, the main question to address is the extent to which the formation and transport of aerosols and foam from the sea may significantly contribute to the total atmospheric deposition of PFASs over land.

In an investigation for Region Syddanmark, NIRAS (2023) investigated the concentration of $PFAS_{22}$ in groundwater, surface water and soil at the island of Fanø and how this varies with the distance to the sea. For surface water, the concentration decreased from 260 ng/L closest to the sea to 17 ng/L at 3 km from the sea. A similar pattern showing decreasing concentrations over increasing distances to the sea was observed for groundwater samples, whereas for soil samples, no clear correlation between concentrations and distances to the coast was observed.

Similar results were obtained by NIRAS (2022) in an investigation for Lemvig Municipality. Data for PFAS4 showed that the concentration in the groundwater decreased with higher distance from the sea and, even at a distance of 300 m, the concentrations had decreased significantly. However, all samples from 300-550 m from the sea exceeded Danish quality criteria for groundwater. For drain water and surface water, a similar trend was observed, and the concentrations markedly decreased for drainage wells located more than 500 m from the sea. For soil, a correlation between concentrations and distances to the coast was observed. In the conceptual understanding of the phenomenon, NIRAS (2022) suggests that the increased concentrations in the groundwater close to the sea is partly a consequence of seawater penetrating the coastal groundwater.

None of the identified investigations allow for estimation of the atmospheric deposition per m^2 in the coastal areas. Quantification is also made difficult by variations observed where significant formation of foam is seen during storm events. The deposition appears to be local and may influence the overall deposition at a distance of up to one to two kilometers from the coast. The phenomenon is most pronounced at the West Coast of Jutland. All in all, it is estimated in this study that an area of 1,000-2,000 km^2, representing 2-4% of the total area of Denmark, may experience elevated atmospheric deposition from aerosols and sea foam, but there is no basis for estimation of how much this source could contribute to total deposition. Both investigations quoted above did not observe a correlation between soil concentrations and distances to the coast, which may indicate that the elevated atmospheric deposition on an annual basis may be less significant, but that actual measurements of annual deposition of PFASs in coastal areas would be needed for a closer assessment.

No data are available to indicate the sources of the PFASs in coastal waters, which may be a combination of local land-based sources, atmospheric deposition and transport by sea

currents. Along the west coats of Jutland, the Jutland Coastal Current (Danish: Jyllandstrømmen"), which moves northward from the German Bight, contains higher concentrations of nutrients than the rest of the North Sea (Christensen et al., 2004). This situation results in a gradient of nutrient concentrations along the west coast. The German Bight receives nutrients from the large European rivers, primarily the Elbe and the Rhine. It is not shown whether similar transport takes place for PFASs. Ahrens et al. (2009) found that the rivers Elbe, Weser and Ems had a significant influence on the distribution of most PFASs in the German Bight, with maximum PFAS concentrations found in their estuaries and concentrations decreasing with increasing distance from the coast. The distribution of PFASs in grass and surface water in coastal zones of Denmark (Danish Nature Agency, 2023) does not indicate any gradient along the West Coast of Jutland, with concentrations decreasing from the south to the north. The highest concentrations in both grass and surface water are found in an area between the Limfjord and Ringkøbing Fjord, which may rather indicate that local sources have an influence on the deposition.

PFASs in the air and the importance of long-range transport

No investigations of PFASs in the air in Denmark have been identified. Bossi and Ellerman (2023) summarise the overall pattern as regards types of PFASs in the air as follows: *"Both ionic and neutral PFAS are present in the atmosphere. Concentrations of neutral PFAS are usually much higher than those of ionic PFAS. Neutral PFAS include FTOHs, FOSA and FOSE, while ionic PFAS include PFCAs (e.g. PFOA), PFSAs (e.g. PFOS), and the novel PFAS (e.g, HFPO-DA with trade name Gen-X). Neutral PFAS are characterized by different vapor pressures and thus they are partitioned between gas and particulate phase depending on the temperature. In general, field measurements of PFAS confirm that partitioning from the gas phase to the particulate phase is more favorable with increasing carbon atom chain length and decreasing temperature. Ionic PFAS are expected to be present in their non-volatile anionic form in particle phase."* Regarding their further fate the authors note: "*Once in the atmosphere the neutral precursors undergo oxidation resulting in formation of more polar ionic compounds (PFCAs and PFSAs). Atmospheric residence time for FTOH is between 50 and 70 days for photodegradation to the corresponding ionized PFAS (Ellis et al., 2004). Ionic PFAS are characterized by low volatility and higher water solubility than the neutral precursors and in the atmosphere are mostly bound to particle phase."*

Study from Northern Germany. In a study from Northern Germany, Drejer and Ebinghaus (2010) found that average total PFAS concentrations in and around Hamburg (180 pg/m^3) were higher than those observed in the German Bight (80 pg/m^3). In the German Bight, minimum-maximum gas-phase concentrations of 17-82 pg/m^3 for ΣFTOH, 2.6-10 pg/m^3 for ΣFTA, 10-15 pg/m^3 for ΣFASA, and 2-4.4 pg/m^3 for ΣFASE were determined. In the vicinity of Hamburg, minimum-maximum gas-phase concentrations of 32-204 pg/m^3 for ΣFTOH, 3-26 pg/m^3 for ΣFTA, 3-18 pg/m^3 for ΣFASA, and 2-15 pg/m^3 for ΣFASE were detected. Concentrations of perfluorinated acids (PFAAs) were in the range of 1-11 pg/m^3. FTOH clearly dominated the substance spectrum; 8:2 FTOH occurred in the highest proportions. According to the authors, air mass back trajectories, cluster, and correlation analyses revealed the air mass origin; medium to long range atmospheric transport was the governing parameter for the amount of PFASs in ambient air. Southwesterly located source regions appeared to be responsible for elevated PFAS concentrations, while local sources appeared to be of minor importance.

5.1.2 TFA and related substances

No Danish data for deposition of TFA have been identified but one study of deposition of PFAS pesticides is available.

Deposition of plant protection products with PFAS active substances. The national monitoring program NOVANA includes monitoring of atmospheric wet deposition of a number of plant protection products (Ellermann et al. 2021, 2022). Among the plant protection products

which were measured in concentrations above the detection limit in 2019 and 2020, Diflufenican was the only one among the plant protection products with PFAS active substances listed in section 2.2.16. The annual deposition of Diflufenican at two locations (Septrup Sande and Risø) was in 2019 0.6 and 0.7 µg/m^2, respectively, and 1.1 and 1.7 µg/m^2 in 2020 (the plant protection products were not measured in 2021). The average of the four measurements was used as the best estimate for further calculations. Diflufenican is the pesticide with PFAS active substances used in the largest quantities in Denmark; during 2019-2021, it accounted for 43% of the total quantity of PFAS active substances in plant protection products with an average consumption of 86 t/y. No data are available on the wet deposition of plant protection products over the sea.

An estimate of TFA deposition is based on literature data from other countries reviewed below.

Review of data on deposition in other countries

TFA deposition in Germany. Freeling et al. (2022) provide a comprehensive overview of the occurrence of TFA in precipitation in Germany. In total, 187 precipitation samples, collected over the course of 12 consecutive months at eight locations across Germany, were analyzed. The median, the estimated average, and the precipitation-weighted average TFA concentration of all analyzed wet deposition samples were 210, 703 and 335 ng/L, respectively. For Germany, an annual wet deposition flux of 190 µg/m^2 or approximately 68 t/y was calculated for the sampling period from February 2018 to January 2019 using the precipitation-weighted averages. The authors note that 2018 was a year with exceptionally low precipitation in Germany and that the total may be higher in other years. According to the authors, the total annual deposition flux for 2018 was substantially higher than the annual wet deposition fluxes of 22 and 30 t/y calculated for Germany for the periods from April 1995 to March 1996 and October 1995 to September 1996, respectively. This indicates a considerable increase in the atmospheric wet deposition of TFA in Germany over the last two decades. The campaign revealed a pronounced seasonality of the TFA concentration and wet deposition flux of collected samples with higher atmospheric deposition of TFA during summer. The authors note that the observed seasonal variations in the TFA concentration/flux suggest that the atmospheric oxidation of volatile precursors is a major source of TFA in the atmosphere and in precipitation and that some HFCs and HFOs are considered to be increasing sources of TFA in precipitation. Annual totals of the TFA wet deposition ranged between locations from 91.4 µg/m^2 to 401 µg/m^2. The low wet deposition flux at one site could be explained by the low amount of annual rainfall at the site and, therefore, a lower potential for TFA scavenging and local TFA deposition. The three sites with the highest annual TFA wet deposition fluxes are all located in densely populated regions in Germany. The authors discussed possible sources that may cause higher concentrations in urban locations. One potential source was generation of TFA through the thermolysis of fluorinated polymers, especially in high-temperature applications such as combustion engines and ovens used extensively in urban and industrial areas. The authors did not find that higher emissions of PFAS-gases in urban environments could be the explanation, as the long atmospheric lifetime (multiple years) of the gases would cause them to be well mixed in the atmosphere. According to Freeling et al. (2022), it is estimated that dry deposition typically accounts for about 25% of the atmospheric TFA deposition. Dry deposition has to be added to the reported wet deposition in order to properly estimate the total atmospheric deposition of TFA.

TFA deposition in the USA. The concentrations of 15 PFASs in precipitation were measured at six locations in the Ohio-Indiana region of the USA by Pike et al. (2021) during the summer of 2019, and compared to samples collected at a distant site in northwest Wyoming. Total PFAS concentrations were in the range of 50-850 ng/L, with trifluoroacetic acid (TFA) being the dominant compound representing approximately 90% of the total (totals excl. TFA ranged approximately from 5 to 85 ng/L). According to the authors, concentrations of PFOA and PFOS were similar to amounts observed over the past 20 years, indicating persistence in the

atmosphere. According to the authors, statistically significant differences ($p < 0.05$) in PFAS profiles across sites separated by 10-100 km indicated that local point sources strongly contributed to wet deposition.

Fluoropolymers as sources of TFA in precipitation. Fluoropolymers are employed in a wide variety of thermal applications, especially in areas of harsh chemical and high thermal stress, such as cookware, ovens, industrial and car engines, heat exchanger and high-temperature circuits. A study from China estimated that thermolysis of fluoropolymers could contribute 0.6-6.1 ng/L in rainwater in Beijing and account for 1.6-14% of the total TFA burden in the rain (Cui et al., 2019).

5.1.3 Polymeric PFASs

No data on deposition of fluoropolymers in the form of microplastics have been identified. The significance of microplastics deposition was demonstrated by Brahney et al. (2020), which estimated a deposition of 1,185-3,733 metric tons of plastic per year over 496,350 km^2 of protected areas in the western USA. An indication of the potential order of magnitude of fluoropolymer deposition in Denmark could be calculated assuming the same deposition flux as measured by Brahney et al. (2020) and assuming that fluoropolymers comprise 0.1% of microplastics, corresponding to these polymers' share of the EU total plastics consumption. On this basis it can be estimated that annual deposition would be in the range of 100-300 kg/year. Due to the high level of uncertainty as to the representativeness of the data, the estimate was not used further in this analysis, but it indicates that the deposition of fluoropolymers cannot be considered insignificant.

5.2 Estimated atmospheric deposition

For estimation of total atmospheric deposition in Denmark, the estimated average wet and dry deposition per m^2 was multiplied by the land area of 43.000 km^2 and the area of the Danish Waters of 105.000 km^2 (Ellermann et al., 2021). Of the 43.000 km^2 land area, 2,565 km^2 is equipped with diversion to sewers.

PFAAs and precursors. In the absence of Danish measurements of a wider range of PFASs, the estimate was based on the available data from Northern Germany and Sweden. The study of Dreyer et al. (2010) included 34 PFASs in total. The ∑34 PFAS concentration in the rainwater varied between 1.6 ng/L and 48.6 ng/L. The average of the total concentration was estimated at approximately 8.8 ng/L. With an average annual precipitation of 750 l/m^2 in Denmark, this corresponds to wet deposition of 6.6 $\mu g/m^2$. Swedish studies of ∑16 PFASs found concentrations in rain from remote areas in the range of 0.90 to 5.88 ng/L, while the concentration in Stockholm ranged from 0.95 to 6.39 ng/L (Johansson et al. 2019, Filipovic et al., 2015). Mean values were not reported, but the data did not indicate major differences between remote and urban areas. A study from Japan measured total concentration of three FTOHs (not included in the above-mentioned studies) at 3 ng/L (Mahmoud et al., 2009). A screening study from the USA (Kim et al., 2022) indicated that the concentrations of emerging PFASs may be in the 10-1000 ng/L range and approximately 1-2 orders of magnitude greater than conventionally monitored PFAS. Even though the estimates were based on "semi quantification", combined with the results from Japan, they indicate that other PFASs may contribute significantly to the totals. In the absence of quantitative studies including a broad range of PFASs, the mean value of the ∑34 PFASs measured by Dreyer et al. (2010) were multiplied by 2 in this study to take into account FTOHs and emerging PFASs. This was further multiplied by 1.1 to include dry deposition. The flux over the sea is roughly estimated to be half the flux over land.

Polymeric PFASs. As indicated above, no data on atmospheric deposition of polymeric PFASs have been identified.

TFA related PFASs. In the absence of Danish data on deposition, the German data for 2018/19 are used as a best estimate. The precipitation-weighted average wet deposition flux of 190 µg/m^2 was recalculated into a total wet and dry deposition of 253 µg/m^2, under the assumption that the dry deposition represents 25% of total deposition as described by Freeling et al. (2022). The German data indicates that the deposition over remote areas is lower than over urban areas; in the absence of specific data, the deposition per m^2 over the sea was assumed to be half of the deposition over land. This assumption also reflects lower precipitation over the seas.

The total wet deposition of the pesticide Diflufenican over land was estimated at 0.05 t/y. Compared to the average consumption in 2019-21 of 86 t/y, wet deposition corresponds to 0.05%. Data are not available for other plant protection products with PFAS active substances, but it will be roughly assumed that the percentage deposited is the same as for Diflufenican in this study. No data have been identified on deposition of plant protection products with PFAS active substances over the sea.

The total atmospheric deposition of TFA and related substances over land, based on the above-mentioned information, was estimated at 10.3 t/y, while the estimated deposition over sea was estimated at 13.4 t/y. An estimated 0.65 t/y ends up in precipitation directed to the sewer systems.

Table 102. Parameters used for estimation of atmospheric deposition of PFAAs and precursors and TFA related PFASs. No data are available for polymeric PFASs.

Area	**Area** Km^2	Deposition flux g/km^2/year	Deposition, kg/y	Remark
PFAAs and precursors				Deposition flux over land based on wet deposition data from Northern Germany from 2010 for ∑34 PFAS multiplied by 2 to take into account other PFASs and multiplied by 1.1 to take into account dry deposition.
- Land (excl. sewage systems)	40,435	7.3	587	
- Sea	105,000	3.7	762	
- Sewage system	2,565	7.3	37	Deposition flux over sea is assumed to be 50% of flux over land to take into account lower precipitation and higher distance to sources. The estimated deposition is estimated to be within the right order of magnitude (medium uncertainty).
TFA related substances				Deposition flux over land is mainly based on data on wet deposition of TFA in Germany 2018/19 multiplied by 1.33 to take into account dry deposition. A small fraction is based on Danish data for plant protection products.
- Land (excl. sewage systems)	40,435	253	10,300	
- Sea	105,000	127	13,400	
- Sewage system	2,565	253	654	Deposition flux over sea is assumed to be 50% of flux over land to take into account lower precipitation and higher distance to sources. The estimated deposition is estimated to be within the right order of magnitude (medium uncertainty).

Summary. Concentrations, deposition rates and total deposition by group of PFASs are summarised in the table below.

Table 103. Estimated total deposition of PFASs by group, over land and sea in Denmark in 2021

Group of PFAS	Wet and dry deposition, g/km² land / sea	Total deposition, kg/y			
		Land	Sea	Sewage systems	Total (rounded)
PFAAs and precursors	7.3 / 3.7 *	587	762	37	1,400
TFA related PFASs	253 / 127 *	10,300	13,400	654	24,400.
Polymeric PFASs	n.d.	n.d.	n.d.	n.d.	n.d
Total PFASs (rounded)		10,900	14,200	690	25,800

* Assumed flux over land and sea, respectively.

6. Summary and discussion

6.1 Input of PFASs to society in Denmark

The total input of PFASs to society in Denmark in 2021 is summarised in Table 104.

PFAAs and precursors. The total input to society of PFAAs and precursors (incl. side-chain fluorinated polymers) is estimated at 370 t/y. Of this, TULAC applications account for 66%. Side-chain fluorinated polymers account for the major part of PFAAs and precursors in the final TULAC products. Construction materials account for another 5% which are also predominantly attributed to side-chain fluorinated polymers. Food contact and packaging materials account for 12%, and for this application area, the majority of the PFAAs and precursors are also side-chain fluorinated polymers to provide repellent performance. The results demonstrate the need for including analysis of side-chain fluorinated polymers and the fluorotelomer precursors (which are the initial degradation products, if the further fate of the substances in waste streams and releases to the environment are to be followed.

TFA related substances. The total consumption of TFA related PFASs is estimated at 660 t/year, with the largest contribution from PFAS gases (primarily HFCs and HFOs), which made up 73% percent of total consumption, followed by PFAS active substances in pesticides (26%) and pharmaceuticals for humans (1%). There have been no data available for a calculation of the consumption of veterinary medicines. Compared to the calculation of the consumption of PFAA and their precursors, the estimated consumption of PFASs for the application areas covered by this group is very certain, as it is based on actual consumption in Denmark according to Danish statistics. The extent to which pesticides and pharmaceuticals with active substances that fall under the PFAS definition are manufactured in Denmark has not been investigated as confi-dentiality issues are then encountered.

Polymeric PFASs (excl. side-chain fluorinated polymers). Fluoropolymers are not manufactured in Denmark. The total consumption of polymeric PFASs is calculated at 1,690 t/year, with the largest contributions arising from clothing and textiles, but also with significant contributions from a wide range of application areas. An in-depth study of the use of polymeric PFASs in production processes in Denmark was not carried out, but available information from industry organisations and companies contacted indicates that the total consumption of fluoropolymers for production processes in Denmark roughly corresponds to the EEA average. The total import of fluoropolymers (PTFE and fluoroelastomers) for use in production in Denmark was approx. 1,050 t/year in 2021. A significant fraction of production consists of producing items that are surface-treated with fluoropolymers and which are used in a wide range of sectors.

Table 104. Estimated input of PFASs to the society in Denmark in 2021

Applications area	Input to the society, t/y			Uncertainty ranking
	PFAAs and pre-cursors	TFA related substances	Polymeric PFAS	
Apparel	100	0	400	Medium
Textiles, upholstery, leather, and carpets	72	0	520	Medium
Food contact materials and pack-aging	50	0	230	High
Metals plating / metal products	0.4	0	10	High
Consumer mixtures	0.4	0	0	High
Cosmetics	0.4	0	0	High
Ski wax	0.02	0	0	High
Medical devices	30	0	100	High
Transport sector	7	0	140	High
Electronics & manufacture of semi-conductors	15	0	40	High
Energy sector	4	0	40	High
Construction materials/products	22	0	90	High
Lubrification	0	0	20	High
Oil-gas & other extraction	0.13	0	102	Medium
Firefighting foams	2.3	0	0	High
PFAS gas uses	0	480	0	Low
Pesticides	0	173	0	Low & high
Pharmaceuticals for human use*	0	6.5	0	Medium
Unintentional uses (except for re-cycled food contact materials and packaging)	0.002	n.d	n.d.	High
Sum (rounded)	300	660	1,690	

Uncertainty ranking: Low : The actual value is most likely within a range of ±25% ; Medium: The actual value is most likely more than 1/3 and less than three times the best estimate. High: The actual value may be less than 1/3 or more than 3 times the best estimate.

* No data on the consumption of PFAS active substances in veterinary pharma have been available.

6.2 Emission to the environment and substance balances

The following section includes summaries of releases to the environment and substance balances for the three groups of PFASs.

It should be noted that quantities are estimated on the basis of the weight of substances used. In the case that substances are broken down, the weight of those degradation products that fall under the PFAS definition are generally lower than the weight of the precursors.

The delineation between the three groups is not completely clear. The fluoropolymers may form TFA and fluorinated gases under certain thermal conditions, even though limited data are available for quantification. Furthermore, some polymeric PFASs that are not fluoropolymers or side-chain fluorinated polymers may have moieties that may be decomposed to PFAAs in the same way as the side-chains of the side-chain fluorinated polymers. However, in the

context of overall uncertainties, this factor is not expected to significantly change the conclusions of the study.

For many of the flows, sufficient data have not been available for their estimation, even taking into account their associated high uncertainties. In the tables and flow charts below, for flows without data, the description distinguishes between n.d. and “negl.”. N.d. indicates that no quantitative data are available, but the that the flow may be significant. “Negl” (negligible) indicates that no quantitative data are available, but from the available information, the flow is likely negligible in comparison with the overall flow of the substances.

6.2.1 PFAAs and precursors

The estimated outputs of PFAAs and precursors from society in Denmark in 2021 are summarised in Table 105. Data on quantities directed to sewage are not included in the table, as it is not a final output. However, this is addressed in Table 91.

Emission to air. The total emissions to air are estimated at 2,240 kg/y. A comparison with the total estimated atmospheric deposition of 1,400 kg/y indicates that the estimated emissions are of the right order of magnitude, although it should be noted that both estimates are uncertain. Emissions from incineration of both municipal solid waste and sewage sludge, which have been a subject of discussion for some years, are estimated to be less than 1 kg and negligible as compared to the total emissions to air. Within the waste treatment sector, significantly higher emissions are estimated for landfills and sewage treatment plants.

The major types of PFASs emitted are the volatile substances such as the FTOHs. These are also among those PFASs emitted from mixtures and articles which account for the majority of all emissions to air. It should be noted that emissions from mixtures and articles, are estimated using generic Environmental Release Categories (ERCs) used for the PFAS restriction proposal, and which represent worst case emission factors.

Relatively high levels of neutral PFASs in indoor air as compared to outdoor air have been demonstrated in several publications (e.g., reviewed by Fromme et al., 2015). The highest levels are found for FTOHs and FTACs. Similar levels are found in homes, schools and offices while for other indoor spaces, clearly higher PFAS levels were reported in shops selling leather, textiles or shoes and in furniture shops and stores offering outdoor equipment (Fromme et al., 2015). Barber et al. (2007) found that concentrations of neutral PFASs were several orders of magnitude higher in indoor air than outdoor air and suggested that homes are likely important diffuse sources of PFASs to the atmosphere. No studies quantifying the annual emission of PFASs from indoor environments have been identified, but the available data supports the idea that emissions to air from products are potentially a significant source.

Releases to soil and surface water. The major sources of releases to soil and surface water are estimated to be apparel and fire-fighting foams, which by far exceed releases to soil in sewage sludge and to surface water from sewage treatment plants. The side-chain fluorinated polymers are not measured in the traditional methods used for monitoring PFASs in the environment. Apart from three studies of one specific side-chain fluorinated polymer in sewage sludge (Scotchgard™) and agricultural soil supplied with sewage sludge, no data are available to assess whether the estimated releases are realistic. For fire-fighting foams, the releases were estimated using the ERCs and observations applied in the PFAS restriction proposal, and it is uncertain to what extent they actually reflect the situation in Denmark.

The main contribution to the releases to soil and surface water for the use category “Textiles, upholstery, leather, and carpets” is from technical textiles (e.g. canvas, awnings, tarps, tents, sails, rope) for outdoor applications.

Once released to the environment, side-chain fluorinated polymers slowly degrade, and the side-chains may stay in the environment for centuries. According to OECD (2022b) *"Therefore, the degradation half-lives of acrylate and urethane SCFPs in the environment and biota will remain to some extent uncertain, in part reflecting real-world variability associated with the factors described above. Still, more of this uncertainty is because the characterization of many of these parameters are not available in the public domain (e.g., molecular size and specific surface areas of SCFP particles in commercial formulations) and may change over time (e.g., molecular size decreases when the degradation mechanism B occurs). Nevertheless, it can be concluded that these SCFPs generally will degrade under environmental conditions, with half-lives often falling roughly at a century or less, and thus serve as a long-term source of non-polymeric PFASs in the environment and biota."*

Releases from sewage treatment plants. The total releases of PFAAs and precursors from sewage treatment plants are estimated at 294 kg/y. Releases of $PFAS_4$ and ∑16 PFAS used for monitoring are estimated at 5.9 kg/y and 30.0 kg/y, respectively. The results illustrate that the majority of the PFAAs and precursors in the sewage consist of side-chain fluorinated polymers and non-polymeric precursors that are not included in the conventional monitoring of PFASs. Estimates of PFAAs and precursors (mainly side-chain fluorinated polymers) directed to sewage, based on data on the uses of apparel and other TULAC application and applied emission factors, indicate that discharges to STPs and the likely releases from STPs may be significantly higher than estimated in this study.

Export. The majority of the outputs from society are exported with articles for recycling abroad and destruction of PFASs in incinerators. The PFASs principally follow the apparel for reuse abroad; the final destinations of the PFASs are likely landfills, waste dumps and open fires. In a report from the Nordic Council of Ministers on fate, benefits and impacts of exports of textiles from Nordic countries, for the purposes of the disposal model, it is assumed that in developing countries, 50% of reused Nordic textiles eventually end up in open landfill and 50% end in open fires (Watson et al., 2016).

Destruction. It is estimated that about 70% of the PFAAs and precursors in output from society is destroyed in incineration. On the basis of the quantities disposed of for incineration and the outputs from the incinerators, the destruction efficiency for PFAAs and precursors was estimated at 99.9989%. Although the estimate is uncertain, it indicates that the destruction efficiencies for PFASs is of the same order of magnitude as the reported destruction efficiencies for persistent organic pollutants.

Table 105. Estimated outputs of PFAAs and precursors from society in Denmark in 2021 excl. export in products

	Outputs from society, kg/y						Uncertainty ranking, releases *
	Air	Soil	Surface water	Landfill, DK	Export with	Destruction **	
Application areas:							
Apparel	251	2,339	220	-	35,090	49,000	High
Textiles, upholstery, leather, and carpets ***	36	1,037	97	-	-	70,000	High
Food contact materials and packaging ***	25	-	-	-	6,394	40,000	High
Metals plating/metal products ***	-	-	-	-	166	83	High
Ski wax ***	1	6	6	-	0	0	High
Medical devices ***	600	-	-	-	0	27,000	High
Transport sector ***	4	112	-	1,828	677	4,266	High
Electronics & manufacture of semi-conductors ***	10	0	-	0	3,507	877	High
Energy sector ***	270	0	-	0	409	1,051	High
Construction materials/products ***	970	20	-	4,008	0	16,000	High
Lubrification ***	4	0	-	-	0	93	High
Oil-gas & other extraction ***	10	0.68	11	-	2	6	High
Firefighting foams	0	856	1,056	-	-	-	High
Waste management:						-	
Incineration (excl. sewage sludge incineration)	0.09	-	0	2.0	0.5	-	Medium
Landfills	25	-	2.5	Not relevant	-	-	Medium
Other waste disposal	-	-	1.3	-	-	-	Medium
Municipal sewage treatment plants (excl. sludge treatment)	15	-	294	-	-	-	Medium
Discharge from overflow	-	-	10	-	-	-	Medium
Discharge from separate sewage systems	-	-	4	-	-	-	High
Sewage sludge treatment	15	24.8	-	-	-	2	Medium
Manure	-	2.4	-	-	-	-	Medium
Total quantified (rounded)	2,240	4,390	1,700	5,840	46,200	208,000	-
% of total	0.8%	2%	1%	2%	17%	78%	

* The uncertainty ranking concerns releases to the environment only. The uncertainties on estimates of quantities directed to landfill, exported and destroyed are generally lower and reflect the uncertainties on the input to society. Uncertainty ranking: Low : The actual value is most likely within a range of ±25%.

Medium: The actual value is most probably more than 1/3 and less than three times the best estimate.
High: The actual value may be less than 1/3 or more than 3 times the best estimate.

** Destruction is by waste incineration, allocated to the different application areas in this study.

***Based on default worst-case REACH ERCs.

"-" The quantity is considered most likely to be insignificant, but it cannot be excluded that some releases take place. n.d.: no data but releases may be significant.

The overall substance balance for the PFAAs and precursors is illustrated in Figure 4. There is a large discrepancy between the 9 t/y estimated to be directed to sewage treatment on the basis of estimated consumption and the estimate 0.75 t/y based on measured inputs/outputs, even when the presence of non-targeted precursors and side-chain fluorinated polymers are taken into account. The reason may be either that the presence of side-chain fluorinated polymers in the sewage is underestimated or that a smaller fraction of the PFASs in apparel and other applications ends up in the sewage than estimated. A part of the explanation may also be that degradation of 1 kg of side-chain fluorinated polymers result in a lower quantity of PFAS degradation products illustrated by the fact that the total fluorine content of the side-chain fluorinated polymers is significantly higher than the total fluorine content of degradations products such as the fluorotelomers and PFAAs.

Accumulation in the use phase in society is estimated at 22 t/y, indicating a steady state situation where outputs broadly balance the inputs.

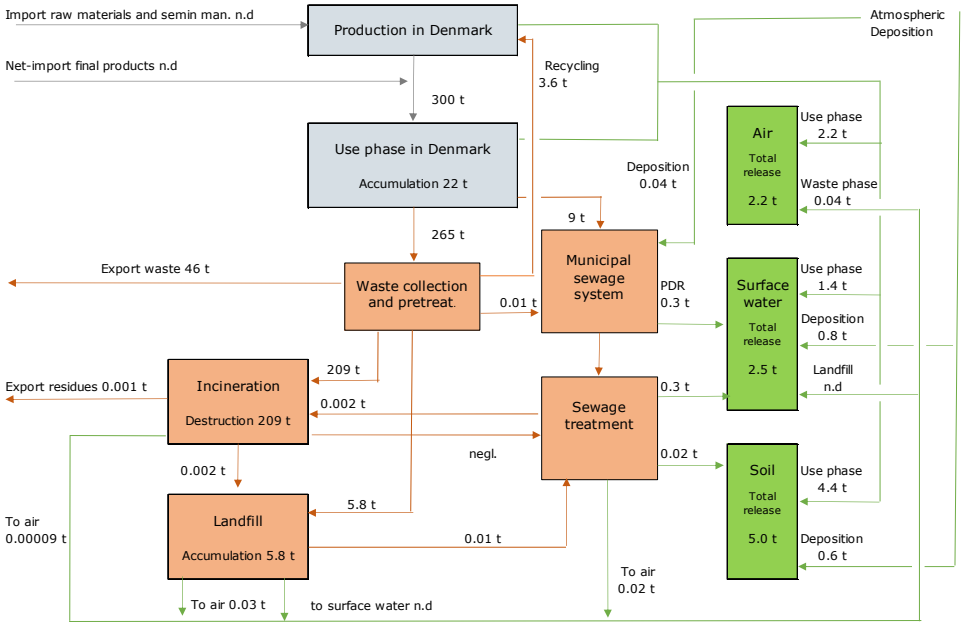


Figure 4. Substance flow balance for PFAAs and precursors in Denmark in 2021.

In an attempt to put the releases from wastewater treatment in Denmark into perspective, data on inflow and outflow of PFASs to the Baltic Sea through the Danish Straits were reviewed. HELCOM (2020), in a document on PFOS and other PFASs in the Baltic Sea, makes reference to Filipovic et al. (2013) as concerns a mass balance for PFASs for the Baltic Sea. Filipovic et al. (2013) estimated the total outflow of $PFAS_4$ from the Baltic Sea through the Danish Straits at 734 kg/y, while the inflow from the North Sea through the straits was estimated at 157 kg/y[31]. The main source of the $PFAS_4$ to the Baltic Sea is atmospheric deposition and

[31] Concentrations of individual substances are partly represented by single values and partly by ranges. In the latter case, the midpoint is used for the estimation in this study.

riverine inflow (Filipovic et al., 2013). Data are not available for other PFASs. For comparison, the total estimated discharge of $PFAS_4$ from Danish STPs in 2021 is estimated at 5.9 kg/y n the current study (see Table 97). No data are available to estimate the possible changes in the transported quantities of $PFAS_4$ from 2013 to 2021.

6.2.2 TFA related PFASs

The estimated outputs of TFA related substances from society in Denmark in 2021 are summarised in Table 106.

Emission to air. Emission to air is totally determined by the emissions from the applications of fluorinated gases, which represent nearly 100% of the 200 t/y estimated to be emitted to air. In addition, some non-quantified emission of PFAS gases may take place by incineration of fluoropolymers. As well, TFA may be formed by thermolysis of fluorinated polymers in high-temperature applications such as combustion engines and ovens. The total atmospheric deposition of the substances (nearly 100% TFA) is estimated at 24 t/year. The main source of the TFA in the atmosphere is PFAS gases, but the gases are generally not 100% degraded to TFA. The yield of TFA from HFC-134a (the largest volume commercial HFC) is about 20% [32]. The long atmospheric lifetime of the gases of multiple years leads them to be well mixed in the atmosphere, and a link between the quantities emitted from Denmark and atmospheric deposition cannot be made.

Releases to soil. The main source of releases to soil is the use of plant protection products with active substances with a $-CF_3$ moiety, which accounted for releases of 172 t/y. The plant active substances may to some extent be degraded to TFA, but the total amount of TFA formed by the ultimate degradation of the active substances is not known. Sewage sludge represents a minor contribution to the total. Application of manure on agricultural land may spread veterinary pharmaceuticals and their metabolites. In the absence of data on the quantities of veterinary pharmaceuticals falling under the PFAS definition used in Denmark, it has not been possible to quantify this source.

Releases to surface water. Municipal STPs constituted the main source of direct releases to surface water. The main source of the substances in the sewage is pharmaceuticals with one or more $-CF_3$ moieties and their metabolites. Some uncertainties exist as to the quantities of the pharmaceuticals and metabolites in the sewage and sludge. The estimates of PFAS pharmaceuticals discharged to sewage treatment plants, formed on the basis of estimated quantities sold in Denmark, indicate that the quantities of the pharmaceuticals and metabolites in the sewage and sludge may be underestimated.

[32] https://www.fluorocarbons.org/wp-content/uploads/2016/09/EFCTC-Special-Review-on-TFA-2017_07_11F.pdf

Table 106. Estimated outputs of TFA related PFASs from society in Denmark in 2021 excl. export with products

	Outputs from society, kg/y						Uncertainty ranking, releases *
	Air	Soil	Surface water	Landfill, DK	Export with waste	Destruction **	
Application areas:							
PFAS gas uses	200,000	-	-	-	-	45,000	Low
Pesticides	86	172,000	-	-	-		Low
Veterinary pharmaceuticals ***	-	n.d.	-	-	-		n.d.
Waste management:							
Incineration (Excl. sewage sludge incineration)	n.d.	-	-	n.d.	n.d.	**	High
Landfills	n.d.	-	2	Not relevant	-	0	High
Municipal sewage treatment plants (excl. sludge treatment)	-	-	592	-	-	0	Medium
Discharge from overflow	-	-	20	-	-	0	Medium
Discharge from separate sewage systems	-	-	71	-	-	0	Medium
Sewage sludge treatment	-	50	-	-	-	5	Medium
Total quantified (rounded)	200,000	172,000	700	-	-	45,000	
% of total	48%	41%	0.2%	0.0%	0.0%	11%	

* The uncertainty ranking concerns the releases to the environment only. The uncertainties on estimates of quantities directed to landfill, exported and destroyed are generally lower and reflect the uncertainties on input to society. Uncertainty ranking: Low: The actual value is most likely within a range of ±25%.

Medium: The actual value is most likely more than 1/3 and less than three times the best estimate.

High: The actual value may be less than 1/3 or more than 3 times the best estimate.

** Destruction is by waste incineration, allocated to the different application areas in this study.

*** The potential releases to soil from the use of veterinary pharmaceuticals are not quantified as no data on the use of veterinary pharmaceuticals with PFAS active ingredients in Denmark or EEA have been available. PFAS active substances in veterinary pharmaceuticals are expected mainly to be spread with manure.

"-" The quantity is considered most likely to be insignificant, but it cannot be excluded that some releases take place. n.d.: no data but releases may be significant.

The overall substance balance for the TFA related PFASs is illustrated in Figure 5. There is a discrepancy between the 6.2 t/y estimated to be directed to sewage treatment plants, based on the estimated consumption of pharmaceuticals and biocides with PFAS active substances, and inputs/outputs estimated at 0.73 t/y on the basis of measured data. It should be noted that the weight of PFAS metabolites would be lower than the weight of the active substances of the pharmaceuticals and biocides. It should be noted that the weight of PFAS metabolites would be lower than the weight of the active substances of the pharmaceuticals and biocides.

Accumulation in the use phase in society is estimated at 236 t/y, which reflects that the current input, primarily of PFAS gases, exceeds total releases.

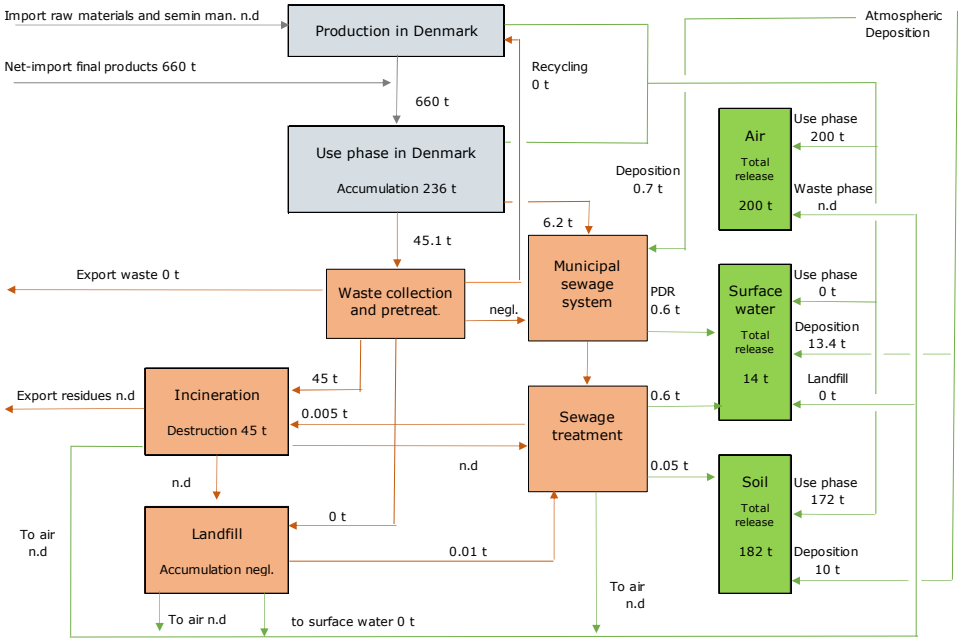


Figure 5. Substance flow balance for TFA related PFASs in Denmark in 2021

6.2.3 Polymeric PFASs

The estimated outputs of polymeric PFASs from society in Denmark in 2021 are summarised in Table 107.

No data have been available on polymeric PFASs in the environment or in waste management flows. While some emission estimates are based on the literature and expert assessment, many emissions are estimated using the generic ERCs used in the PFAS restriction proposal and are considered to represent worst case emission factors.

Emission of microplastics. The majority of the polymeric PFASs are fluoropolymers and fluoroelastomers which mainly consist of plastics or rubber materials. The total emission to the air is estimated at 9 t/y. On the basis of data on deposition of microplastics in the USA and the assumption that fluoropolymers account for 0.1% of total plastics consumption, it can be estimated that the annual deposition in Denmark would be in the range of 0.1-0.3 t/year (see 5.1.3. To put this into perspective, a Danish survey of releases of microplastics estimated the total releases to the environment from the application areas textiles, building materials and cooking utensils at 0.3-1.7 t/y (Lassen et al., 2015). The comparison indicates that the 9 t/y may be an overestimate, but not necessarily totally out of range.

Recycling. An estimated 27% is exported, principally with apparel for recycling, and with metal scrap for recycling of the metals where the polymeric PFASs are destroyed. A small fraction may be exported for recycling of the fluoropolymer, but at EU level, post-consumer recycling of fluoropolymers is essentially non-existent because the fluoropolymers cannot be remelted. No recycling of fluoropolymers in Denmark has been identified.

Destruction. The majority of polymeric PFASs is disposed of for destruction in incinerators. The available studies demonstrate that the destruction does not generate the monitored PFAAs and precursors, but it remains uncertain as to whether some PFAS gases may be formed by the incineration process.

Table 107. Estimated outputs of polymeric PFASs from the society in Denmark in 2021 excl. export with products

	Outputs from society, kg/y						Uncertainty ranking, releases *
	Air	Soil	Surface water	Landfill, DK	Export with waste	Destruction **	
Application areas:							
Apparel	23	1,488	149	-	124,000	173,000	High
Textiles, upholstery, leather, and carpets ***	128	843	84	-	-	308,000	High
Food contact materials and packaging ***	115	-	-	-	92,000	138,000	High
Metals plating/metal products ***	2	-	-	-	8,000	-	High
Medical devices ***	-	-	-	-	20,000	79,000	High
Transport sector ***	70	2,240	-	37,000	14,000	85,000	High
Electronics & manufacture of semi-conductors ***	-	-	-	0	15,000	4,000	High
Energy sector ***	85	-	-	3,600	6,000	11,000	High
Construction materials/products ***	7,450	301	-	-	22,000	38,000	High
Lubrication ***	1,120	-	-	-	18,000	-	High
Oil-gas & other extraction ***	-	-	-	-	29,000	73,000	High
Waste management:							
Incineration (excl. sewage sludge incineration)	-	-	-	-	-	**	n.d.
Landfills	n.d.	-	n.d.	Not relevant	-	-	n.d.
Municipal sewage treatment plants (excl. sludge treatment)	-	-	n.d.	-	-	-	n.d.
Discharge from overflow	-	-	n.d.	-	-	-	n.d.
Discharge from separate sewage systems	-	-	n.d.	-	-	-	n.d.
Sewage sludge treatment	-	n.d.	-	-	-	-	n.d.
Total quantified (rounded) ****	9,000	5,000	200	40,000	346,000	909,000	
% of total	0.7%	0.4%	0.02%	3.1%	27%	69%	

* The uncertainty ranking concerns the releases to the environment only. The uncertainties on estimates of quantities directed to landfill, exported and destroyed are generally lower and reflect the uncertainties on the input to society. Uncertainty ranking: Low: The actual value is most likely within a range of ±25%. Medium: The actual value is most likely more than 1/3 and less than three times the best estimate.

High: The actual value may be less than 1/3 or more than 3 times the best estimate.

** Destruction is by waste incineration, allocated to the different application areas in this study.

***Based on default worst-case REACH ERCs

**** Totals calculated from non-rounded data.

"-" The quantity is considered most likely to be insignificant, but it cannot be excluded that some releases take place. n.d.: no data but releases may be significant.

The overall substance balance for the polymeric PFASs is illustrated in Figure 6.

The accumulation in the use phase in society is estimated at 364 t/y, indicating an increase in the polymeric PFASs accumulated in products in use.

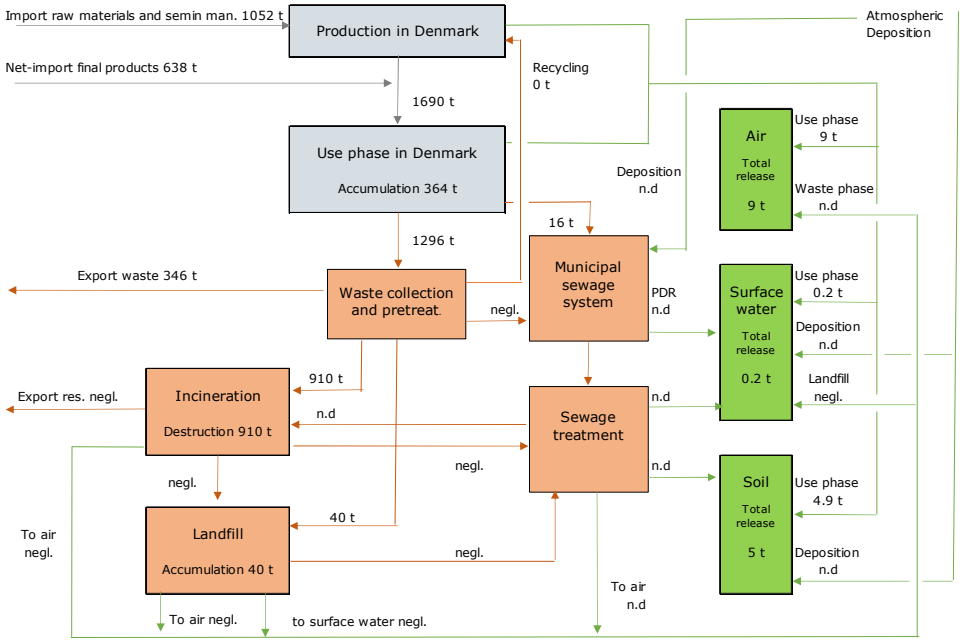


Figure 6. Substance flow balance for polymeric PFASs in Denmark in 2021

6.3 Conclusion and discussion

The group of PFASs that are actually used constitutes hundreds and perhaps thousands of substances in a wide range of applications within all parts of society. Most of these substances do not have a harmonized classification and will therefore only be registered in the Product Registry to a limited extent. In addition, the majority of PFASs in the articles used in society are imported with the articles. It was concluded that an extrapolation from the consumption in the EEA for most product groups would lead to a more reliable estimate than an estimate based on knowledge of the Danish market, as information on market volumes and PFAS content of articles is very limited. For some of the product groups, it was possible to obtain a more reliable estimate of emissions than is achieved using the generic emission factors. This has, for example, been done for clothing, where studies on actual releases were available. However, for a number of the application areas, it was considered that sufficient knowledge to refine the estimates was not available. Despite these uncertainties, the method has proven useful for illustrating the relationship between emissions from the waste phase and from the products' production and use phase.

The study shows very clearly that waste incineration is an effective way to destroy PFASs which are already in circulation, and that emissions from waste and sludge incineration are insignificant as compared to other sources (except for formation of certain fluorinated gases when incinerating fluoropolymers). For the non-polymeric PFASs, releases directly from the use phase are estimated to be the largest sources of releases to the environment. The results indicate that limiting the uses is the most effective way for which releases can be effectively avoided. Side-chain fluorinated polymers are estimated to be the largest contributor to emissions within the group of PFAA and their precursors, but the available knowledge on their occurrence in waste streams and in the environment is very limited. For the polymeric PFASs, the calculations indicate that they will spread as microplastics in waste streams and in the environment to a certain extent, but no studies that can demonstrate their occurrence have been identified.

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Appendix 1. Abbreviations for PFASs mentioned

A list of group abbreviations and specific substance abbreviations used in the report is provided in the tables below.

Table 108. List of abbreviations of groups of PFASs

Abb.	Chemical name
diPAPs	Polyfluoroalkyl phosphoric acid diesters
n:2 FTUCAs *	n:2 Fluorotelomer unsaturated carboxylic acids
n:2 FTOHs *	n:2 Fluorotelomer alcohols
n:2 FTSAs *	n:2 Fluorotelomer sulfonic salts
N:2 FTCAs *	n:2 Fluorotelomer carboxylic acids
FASAs	Perfluoroalkane sulphonamides
FOSE	Perfluorooctane sulfonamides
FOSA	Perfluorooctane sulfonamidoethanols
H-PFCAs	Hydrogen-substituted perfluorocarboxylic acids
PFASs	Per- and polyfluoroalkyl substances
FASAs	Perfluoroalkane sulfonamides
PFAIs	Perfluoroalkyl iodides
PFSAs	Perfluoroalkane sulfonic acids
PASFs	Perfluoroalkane sulfonyl fluorides
PFCAs	Perfluoroalkyl carboxylic acids
PFECAs	Perfluoroalkyl ether carboxylic acids
PFAAs	Perfluoroalkyl acids (e.g. PFCAs and PFSAs)
PFAE	Perfluoroalkylether sulfonic acids

The n designates the number of perfluorinated carbon atoms.

Table 109. List of specific substances' abbreviations

Abb.	Chemical name	CAS No	Chain length	Group name	Group abb.
6:2 FTOH	6:2 Fluorotelomer alcohol	647-42-7	C6	n:2 fluorotelomer alcohols	n:2 FTOHs
4:2 FTS	4:2 Fluorotelomer sulfonate	757124-72-4	C4	n:2 Fluorotelomer sulfonic salts	n:2 FTSAs
6:2 FTS	6:2 Fluorotelomer sulfonate	27619-94-9	C6	n:2 Fluorotelomer sulfonic salts	n:2 FTSAs
6:2 diPAP	6:2 Polyfluoroalkyl phosphate diester	57677-95-9	C6	Polyfluoroalkyl phosphoric acid diesters	diPAPs
8:2 diPAP	8:2 Polyfluoroalkyl phosphate diester	678-41-1	C8	Polyfluoroalkyl phosphoric acid diesters	diPAPs
10:2 diPAP	10:2 Polyfluoroalkyl phosphate diester	1895-26-7	C10	Polyfluoroalkyl phosphoric acid diesters	diPAPs
12:2 di-PAP	12:2 Polyfluoroalkyl phosphate diester	1578186-42-1	C12	Polyfluoroalkyl phosphoric acid diesters	diPAPs
10:2 FTUCA	10:2 Fluorotelomer unsaturated	161094-76-4	C10	n:2 Fluorotelomer unsaturated	n:2 FTUCAs

Abb.	Chemical name	CAS No	Chain length	Group name	Group abb.
	carboxylic acid			carboxylic acids	
6:2 FTAc	6:2 Perfluorotelomer acrylate	17527-29-6	C6	n:2 Perfluorotelomer acrylates	N:2 FTAcS
C4-FN	Heptafluoroisobutyonitrile	42532-60-5	C3	PFAS gases	-
C5-FK	1,1,1,3,4,4,4-Heptafluoro-3-(trifluoromethyl)-2-butanone	756-12-7	C3	PFAS gases	-
PFOSA	Perfluorooctane sulfonamide	754-91-6	C8	Perfluoroalkane sulfonamides	FASAs
MeFOSAA	N-methyl perfluorooctane sulfonamidoacetic acid	2355-31-9	C8	N-methyl perfluoroalkane sulfonamidoacetic acids and salts	-
EtFOSAA	N-ethyl perfluorooctane sulfonamidoacetic acid	2991-50-6	C8	N-ethyl perfluoroalkane sulfonamidoacetic acids and salts	-
MeFOSE	N-methyl perfluorooctane sulfonamidoethanol	24448-09-7	C8	Perfluorooctane sulfonamides	FOSE
PBSF	Perfluorobutane sulfonyl fluoride	375-72-4	C4	Perfluoroalkane sulfonyl fluorides	PASFs
PFDoDA	Tricosafluorododecanoic acid	307-55-1	C14	Perfluoroalkyl carboxylic acids	PFCAs
PFPrA	Perfluoropropanoic acid	422-64-0	C3	Perfluoroalkyl carboxylic acids	PFCAs
PFBA	Perfluorobutanoic acid	375-22-4	C4	Perfluoroalkyl carboxylic acids	PFCAs
PFBS	Perfluorobutane sulfonic acid	375-73-5	C4	Perfluoroalkane sulfonic acids	PFSAs
PFDA	Perfluorodecanoic acid	335-76-2	C10	Perfluoroalkyl carboxylic acids	PFCAs
PFDoDA	Perfluorododecanoic acid	307-55-1	C12	Perfluoroalkyl carboxylic acids	PFCAs
PFDoS	Perfluorododecanoic sulfonic acid	79780-39-5	C12	Perfluoroalkane sulfonic acids	PFSAs
PFDS	Perfluorodecane sulfonic acid	335-77-3	C10	Perfluoroalkane sulfonic acids	PFSAs
PFHpA	Perfluoroheptanoic acid	375-85-9	C7	Perfluoroalkyl carboxylic acids	PFCAs
PFHpS	Perfluoroheptane sulfonic acid	375-92-8	C7	Perfluoroalkane sulfonic acids	PFSAs
PFHxA	Perfluorohexanoic acid	307-24-4	C6	Perfluoroalkyl carboxylic acids	PFCAs
PFHxS	Perfluorohexane sulfonic acid	355-46-4	C6	Perfluoroalkane sulfonic acids	PFSAs
PFNA	Perfluorononanoic acid	375-95-1	C9	Perfluoroalkyl carboxylic acids	PFCAs
PFNS	Perfluorononanoic sulfonic acid	68259-12-1	C9	Perfluoroalkane sulfonic acids	PFSAs
PFOA	Perfluorooctanoic acid	335-67-1	C8	Perfluoroalkyl carboxylic acids	PFCAs
PFOS	Perfluorooctane sulfonic acid	1763-23-1	C8	Perfluoroalkane sulfonic acids	PFSAs
PFOSA	Perfluorooctane sulfonamide	754-91-6	C8	Perfluoroalkane sulfonamides	FASAs
PFEtS	Perfluoroethanesulfonic acid	354-88-1	C2	Perfluoroalkane sulfonic acids	PFSAs
PFPrS	Perfluoropropane sulfonic acid	423-41-6	C3	Perfluoroalkane sulfonic acids	PFSAs
PFTrDA	Perfluorotridecanoic acid	72629-94-8	C13	Perfluoroalkyl carboxylic acids	PFCAs
PFPeS	Perfluoropentane sulfonic acid	2706-91-4	C5	Perfluoroalkane sulfonamides	FASAs
PTFEDA	Heptacosafluorotetradecanoic acid	376-06-7	C14	Perfluoroalkyl carboxylic acids	PFCAs
PFPeA	Perfluoropentanoic acid	2706-90-3	C5	Perfluoroalkyl carboxylic acids	PFCAs
PFTrDA	Pentacosafluorotridecanoic acid	72629-94-8	C13	Perfluoroalkyl carboxylic acids	PFCAs
PFTrS	Perfluorotridecanesulfonic acid	27619-97-2	C13	Perfluoroalkane sulfonic acids	PFSAs
PFUnDA	Perfluoroundecanoic acid	4234-23-5	C11	Perfluoroalkyl carboxylic acids	PFCAs
PFUnS	Perfluoroundecanoic sulfonic acid	749786-16-1	C11	Perfluoroalkane sulfonic acids	PFSAs
POSF	Perfluorooctane sulfonyl fluoride	307-35-7	C8	Perfluoroalkane sulfonyl fluorides	PASFs

Abb.	Chemical name	CAS No	Chain length	Group name	Group abb.
TFA	Trifluoroacetic acid	76-05-1	C2	Perfluoroalkyl carboxylic acids	PFCAs
TFMS	Trifluoromethanesulfonic acid	1493-13-6	C1	Sulfonic acids	

Appendix 2. Other abbreviations and acronyms

AC	Air conditioning
AFFF	Aqueous Film-Forming Foam
API	Active Pharmaceutical Ingredient
BTP	2-Bromo-3,3,3-trifluoroprop-1-ene
d.w.	Dry weight
ECHA	European Chemicals Agency
EEA	European Economic Area
EOF	Extractable organic fluorine
ERC	Environmental Release Category
f_{OC}	Fraction of organic carbon
HCFC	Hydrochlorofluorocarbons
HCFOs	Hydrochlorofluoro-olefins
HEPA	High Efficiency Particulate Air (filter)
HF	Hydrofluoric acid
HFCs	Hydrofluorocarbons
HFEs	Hydrofluoroethers
HFOs	Hydrofluoro-olefins
HVACR	Heating, ventilation, air conditioning, and refrigeration
LCD	Liquid crystal displays
LOD	Limit of detection
LOQ	Limit of quantification
MBNDK	Mechanical, biological, nitrification, denitrification and chemical
MDI	Metered dose inhalers
MSWI	Municipal solid waste incinerator
OC	Organic carbon
OECD	Organisation for Economic Co-operation and Development
OLED	Organic light-emitting diode
PCC	Post-combustion chamber
PDR	Precipitation-derived releases
PFASs	Per- and polyfluoroalkyl substances
PFC	Perfluorocarbon
POP	Persistent organic pollutant
RAC	Committee for Risk Assessment
RPF	Relative Potency Factor
REACH	Regulation (EC) No 1272/2008)
SCFP	Side-chain fluorinated polymers
SEAC	Committee for Socio-Economic Analysis
SPERC	Specific Environmental Release Category

SFP	Side-chain fluorinated polymer
STP	Sewage treatment plant
TF	Total fluorine
TOP	Total oxidizable precursor
TULAC	Textiles, upholstery, leather, apparel, and carpets
w.w.	Wet weight

Polymeric PFASs:

ECTFE	Ethylenechlorotrifluoroethylene
ePTFE	Expanded polytetrafluoroethylene
ETFE	Ethylene tetrafluoroethylene
FEP	Fluorinated ethylene-propylene
FEP	Fluorinated ethylene propylene
FEPM	Tetrafluoroethylene propylene
FEVE	Fluoroethylene Vinyl Ether Resin
FFKM	Perfluoroelastomers
FKM	Family of fluorocarbon-based fluoroelastomer materials
FKM	Fluoroelastomer
F-PMMA	Fluorinated poly(methyl methacrylate)
PCTFE	Polychlorotrifluoroethylene
PFPE	Perfluoropolyethers
PFA	Perfluoroalkoxyl polymer
PFPEs	Perfluoropolyethers
PTFE	Polytetrafluoroethylene
PTFE	Polytetrafluoroethylene
PVDF	Polyvinylidene fluoride
THV	Terpolymer of tetrafluoroethylene, hexafluoropropylene and vinylidene fluoride

Appendix 3. Data from the Danish Product Registry

The results of a search of substances notified to the Danish Product Registry undertaken on the basis of a gross list of PFASs from the US EPA is shown in the table overleaf.

The results are grouped into the three major groups used for this study based on information in the OECD (2018) list and the US EPA gross list.

For the polymers, the grouping into side-chain fluorinated polymers and other fluoropolymers was done on the basis of the structure category names of the OECD list, which distinguishes between fluoropolymers and various fluorotelomer-based side-chain fluorinated polymers.

[lidt om fortrolighed og behandling af fortrolige data]

Table 110. PFASs maximum import, export and consumption in Danish production, with applications in 2023 (Source: The Danish Product Registry; WEA, 2023)

Cas no.	Substance name /Product type code	Product type	No. of products	No. of companies	Prod/Imp max, t PFAS/y	Exp.max, t PFAS/y	Identified max consumption, t PFAS/y	PFAS group	Perfluoroalkyl chain length
647-42-7	**1-octanol, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-**	**Total**	**49**	**5**	**0.49**	**0.06**	**0.43**	PFAAs and precursors	
	M05	*Paints and varnishes*	*47*	*3*	*0.20*	*0.06*	*0.14*		
754-12-1	2,3,3,3-tetrafluorprop-1-en (HFO-1234yf)	**Total**	**9**	**4**	**18.52**	**5.17**	**13.35**	TFA related	3 (Not OECD but PFAS)
	K55	*Refrigerants*	*9*	*4*	*18.52*	*5.17*	*13.35*		
811-97-2	1,1,1,2-TETRAFLUORETHAN (HFC-134a)	**Total**	**12**	**6**	**61.33**	**32.41**	**28.92**	TFA related	2 (Not OECD but PFAS)
	K55	*Refrigerants*	*9*	*4*	*57.50*	*32.41*	*25.09*		
9002-84-0	Tetrafluorethen polymer	**Total**	**251**	**57**	**15.98**	**2.77**	**13.22**	Polymeric	
	L10	*Glue*	*9*	*3*	*0.10*	*0.00*	*0.10*		
	M05	*Paints and varnishes*	*65*	*12*	*7.00*	*0.07*	*6.93*		
	S45	*Lubricants*	*65*	*27*	*0.68*	*0.04*	*0.64*		
	T15	*Printing inks*	*79*	*5*	*4.00*	*0.27*	*3.74*		
34455-29-3	1-propanaminium, n-(carboxymethyl)-n,n-dimethyl-3-(((3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)sulfonyl)amino)-, hydroxide, inner salt	**Total**	**7**	**4**	**0.14**	**0.003**	**0.14**	PFAAs and precursors	6
	B50	*Fire extinguishers*	*5*	*3*	*0.12*	*0.00*	*0.12*		

Cas no.	Substance name /Product type code	Product type	No. of products	No. of companies	Prod/Imp max, t PFAS/y	Exp.max, t PFAS/y	Identified max consumption, t PFAS/y	PFAS group	Perfluoroalkyl chain length
52550-44-4	Poly(oxy-1,2-ethanediyl), .alpha.-(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)-?-hydroxy-	**Total**	**26**	**5**	**0.59**	**0.54**	**0.05**	PFAAs and precursors	6
65530-70-3	Poly(difluoromethylene), a,a'-(phosphinicobis(oxy-2,1-ethanediyl))bis(.omega.-fluoro-,ammonium salt	**Total**	**38**	**8**	**0.09**	**0.02**	**0.07**	PFAAs and precursors	4;6;8;10;12;14;16;18;20
	M05	*Paints and varnishes*	*34*	*4*	*0.07*	*0.01*	*0.06*		
65530-71-4	Poly(difluromethylene), .alpha-fluoro-.omega.-(2-(phosphonooxy)ethyl)-,monoammonium salt	Total	38	8	0.03	0.00	0.03	PFAAs and precursors	4;6;8;10;12;14;16;18;20
	M05	*Paints and varnishes*	*34*	*4*	*0.03*	*0.00*	*0.03*		
65530-72-5	Poly(difluoromethylene), .alpha.-fluoro-.omega.-(2-(phosphonooxy)ethyl)-, diammonium salt	**Total**	**38**	**8**	**0.10**	**0.01**	**0.08**	PFAAs and precursors	4;6;8;10;12;14;16;18;20
	M05	*Paints and varnishes*	*34*	*4*	*0.09*	*0.01*	*0.08*		
65530-85-0	Poly(difluoromethylene), .alpha.-(dyclohexylmethyl)-.omega.-hydro-	**Total**	**8**	**6**	**0.02**	**0.01**	**0.01**	PFAAs and precursors	
	S45	*Lubricants*	*7*	*5*	*0.02*	*0.01*	*0.01*		
69991-67-9	1-propene, 1,1,2,3,3,3-hexafluoro-, oxidized, polymd	**Total**	**4**	**4**	**0.01**	**0.00**	**0.01**	PFAAs and precursors	
104780-70-3	Siloxanes and silicones, di-me, me 3-(1,1,2,2-tetrafluoroethoxy)propyl, me 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl	**Total**	**10**	**3**	**0.00**	**0.00**	**0.00**	PFAAs and precursors	

Cas no.	Substance name /Product type code	Product type	No. of products	No. of companies	Prod/Imp max, t PFAS/y	Exp.max, t PFAS/y	Identified max consumption, t PFAS/y	PFAS group	Perfluoroalkyl chain length
112281-77-3	Tetraconazol							PFAAs and precursors	Not OECD
115340-95-9	Siloxanes and silicones, dimethyl, methyl 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl	**Total**	**329**	**15**	**0.03**	**0.004**	**0.03**	Polymeric	6
	M05	*Paints and varnishes*	*301*	*12*	*0.03*	*0.004*	*0.02*		
138495-42-8	1,1,1,2,2,3,4,5,5,5-decafluoropentan	**Total**	**4**	**4**	**0.0002**	**0.0002**	**0.00**	PFAAs and precursors	Not OECD
	S45	*Lubricants*	*4*	*4*	*0.0002*	*0.0002*	*0.00*		
753501-43-8	Furan, tetrahydro-, compd. With trifluoroborane (1:1)/oxetane, 3-methyl-3-[(2,2,3,3,3-pentafluoropropoxy)methyl]/polyethylenglycol polymer	**Total**	**6**	**3**	**0.10**	**0.00**	**0.10**	Polymeric	Not OECD
1071022-26-8	Acrylsyre/2-(diethylamino)ethylmethacrylat/eddikesyre/methacrylsyre/2-propenoic acid, 2-methyl-, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl ester polymer	**Total**	**4**	**5**	**0.40**	**0.13**	**0.27**	Polymeric	6
Total, named quantities					**98**	**41**	**57**		
Of which:									
PFAS gasses					*80*	*38*	*42*		
PFAAs and precursors					*1*	*1*	*1*		
Polymeric PFAS					*17*	*3*	*14*		
Substances registered for <4 product types and/or <3 companies:									

Cas no.	Substance name /Product type code	Product type	No. of products	No. of companies	Prod/Imp max, t PFAS/y	Exp.max, t PFAS/y	Identified max consumption, t PFAS/y	PFAS group	Perfluoroalkyl chain length
76-16-4	Hexafluorethan							PFAS gases	2 (Not OECD)
354-33-6	Pentafluorethan (hfc-125)							PFAS gases	2 (Not in OECD)
431-89-0	Propane, 1,1,1,2,3,3,3-Heptafluoro- (HFC-227ea)							PFAS gases	3 (Not OECD)
756-13-8	1,1,1,2,2,4,5,5,5-nonafluor-4-(trifluormethyl)pentan-3-on							PFAAs and pre-cursors	3
865-86-1	1-dodecanol, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,12-heneicosafluoro-							PFAAs and pre-cursors	10
915-76-4	1,3,5-triazine, 2,4,6-tris(heptafluoropropyl)-							PFAAs and pre-cursors	3
1652-63-7	1-propanaminium, 3-(((heptadecafluorooctyl)sulfonyl)amino)-n,n,n-trimethyl-, iodide							PFAAs and pre-cursors	8
2991-51-7	Glycine, n-ethyl-n-((heptadecafluorooctyl)sulfonyl)-, potassium salt							PFAAs and pre-cursors	8
11114-17-3	Fluorad fc 430							PFAAs and pre-cursors	Not OECD
25067-11-2	Hexafluorpropen/tetrafluorethen polymer							Polymeric	
25291-17-2	1-octene, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-							PFAAs and pre-cursors	6
27619-89-2	1-octanesulfonyl chloride, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-							PFAAs and pre-cursors	6
27619-97-2	1-octanesulfonic acid, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-							PFAAs and pre-cursors	6
27905-45-9	2-propenoic acid, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluorodecyl ester							PFAAs and pre-cursors	8
29420-49-3	1-butanesulfonic acid, 1,1,2,2,3,3,4,4,4-nonafluoro-, potassium salt							PFAAs and pre-cursors	4
34454-97-2	1-butanesulfonamide, 1,1,2,2,3,3,4,4,4-nonafluoro-n-(2-hydroxyethyl)-n-methyl-							PFAAs and pre-cursors	4
54302-04-4	1-Propene, 3,3,3-trifluoro-2-(trifluoromethyl)-, polymer with chlorotrifluoroethene and ethene							Polymeric	
54950-05-9	Butanedioic acid, sulfo-, 1,4-bis(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl) ester, sodium salt							PFAAs and pre-cursors	6

Cas no.	Substance name /Product type code	Product type	No. of prod-ucts	No. of com-panies	Prod/Imp max, t PFAS/y	Exp.max, t PFAS/y	Identified max consumption, t PFAS/y	PFAS group	Perfluoroalkyl chain length
60164-51-4	Poly(oxy(trifluoro(trifluoromethyl)-1,2-ethanediyl)), .alpha.-(pentafluoroethyl)-.omega.-(tetrafluoro(trifluoromethyl)eth-oxy)-							Polymeric	
62880-93-7	1-propanesulfonic acid, 2-methyl-2-[[1-oxo-3-[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)thio]propyl]amino]-, sodium salt (1:1)							PFAAs and pre-cursors	6
65530-63-4	Ethanol, 2,2'-iminobis-, compd. With .alpha.-fluoro-.omega.-(2-(phosphonooxy)ethyl)poly(difluoromethylene)(2:1)							PFAAs and pre-cursors	4;6;8;10;12;14;16;18;20
65530-64-5	Ethanol, 2,2'-iminobis-, compd. With .alpha.,.alpha.'-(phosphinicobis(oxy-2,1-ethanediyl))bis(.omega.-fluoro-poly(difluoromethylene)) (1:1)							PFAAs and pre-cursors	4;6;8;10;12;14;16;18;20
65530-69-0	Poly(difluoromethylene), .alpha.-(2-((2-carboxyethyl)thio)ethyl)-.omega.-fluoro-, lithium salt							PFAAs and pre-cursors	4;6;8;10;12;14;16;18;20
65545-80-4	Polyethylenglycolmono(2-(perfluoralkyl)ethyl)ether							Polymeric	4;6;8;10;12;14;16;18;20
67584-53-6	Glycine, n-ethyl-n-((tridecafluorohexyl)sulfonyl)-, potassium salt							PFAAs and pre-cursors	6
67584-55-8	2-propenoic acid, 2-(methyl((nonafluorobutyl)sulfonyl)amino)ethyl ester							PFAAs and pre-cursors	4
67584-58-1	1-propanaminium, n,n,n-trimethyl-3-(((pentadecafluoroheptyl)sulfonyl)amino)-, iodide							PFAAs and pre-cursors	7
67939-95-1	1-propanaminium, n,n,n-trimethyl-3-(((nonafluorobutyl)sulfonyl)amino)-, iodide							PFAAs and pre-cursors	4
68187-47-3	1-propanesulfonic acid, 2-methyl-, 2-((1-oxo-3-((.gamma.-.omega.-perfluoro-c4-16-akyl)thio)propyl)amino) derivs., sodium salts							PFAAs and pre-cursors	4
68298-12-4	1-butanesulfonamide, 1,1,2,2,3,3,4,4,4-nonafluoro-N-methyl-							PFAAs and pre-cursors	5
68298-62-4	2-propenoic acid, 2-[butyl[(heptadecafluorooctyl)sulfonyl]amino]ethyl ester							Polymeric	7;8
68391-08-2	Alkoholer, c8-14-, .gamma.-.omega.-per-fluor-							PFAAs and pre-cursors	6;8;10;12
68957-57-3	1-propanaminium, n,n,n-trimethyl-3-(((undecafluoropentyl)sulfonyl)amino)-, iodide							PFAAs and pre-cursors	5
68957-58-4	1-propanaminium, n,n,n-trimethyl-3-(((tridecafluorohexyl)sulfonyl)amino)-, iodide							PFAAs and pre-cursors	6

Cas no.	Substance name /Product type code	Product type	No. of products	No. of companies	Prod/Imp max, t PFAS/y	Exp.max, t PFAS/y	Identified max consumption, t PFAS/y	PFAS group	Perfluoroalkyl chain length
65530-74-7	Ethanol, 2,2'-iminobis-, compd. With .alpha.-fluoro-.omega.-(2-(phosphonooxy)ethyl)poly(difluoromethylene) (1:1)							PFAAs and precursors	4;6;8;10;12;14;16;18;20
79070-11-4	Poly(difluoromethylene), .alpha.-chloro-.omega.-(2,2-dichloro-1,1,2-trifluoroethyl)-							PFAAs and precursors	
80475-32-7	1-octanesulfonamide, n-(3-(dimethylamino)propyl)-3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluoro-, n-oxide							PFAAs and precursors	6
85857-16-5	Silane, trimethoxy(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)-							PFAAs and precursors	6
86479-06-3	1-(3,5-dichloro-4-(1,1,2,2-tetrafluoroethoxy)phenyl)-3-(2,6-difluorobenzoyl)urea							PFAAs and precursors	Not OECD
88992-45-4	1-propanaminium, 2-hydroxy-N,N,N-trimethyl-3-[(3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl)thiol]-, chloride (1:1)							PFAAs and precursors	6
89780-02-9	1,3-benzenedimethanol, 5-(heptadecafluorooctyl)-.alpha.,.alpha.',.alpha.'-tetrakis(trifluoromethyl)-							PFAAs and precursors	8
103055-07-8	Cga 184699							PFAAs and precursors	3
160901-25-7	Sulfonamides, C4-8-alkane, perfluoro, N-ethyl-N-(hydroxyethyl), reaction products with 2-ethyl-1-hexanol and polymethylenepolyphenylene isocyanate							Polymeric	4;5;6;7;8
162567-79-5	Alcohols, C8-14, perfluoro, reaction products with di-Me, Me hydrogen siloxanes and polyethylene glycol mono-Me ether							Polymeric	8;9;10;11;12;13;14
196316-34-4	2-propenoic acid, 2-methyl-, 2-(dimethylamino)ethyl ester, polymers with .gamma.-.omega.-perfluoro-c10-16-alkyl acrylate and vinyl acetate, acetates							Polymeric	8;10;12;14
203743-03-7	2-propenoic acid, 2-methyl-, hexadecyl ester, polymers with 2-hydroxyethyl methacrylate, .gamma.-.omega.-perfluoro-c10-16-alkyl acrylate and stearyl methacrylate							Polymeric	8;10;12;14
333784-46-6	2-propenoic acid, 2-methyl-, 2-ethylhexyl ester, polymers with maleic anhydride, 2-(((2-mercaptoethoxy)carbonyl)amino)ethyl methacrylate, .gamma.-.omega.-perfluoro-c8-16-alkyl acrylate and stearyl methacryalte							Polymeric	6;8;10;12;14
452080-67-0	Boron, trifluoro(tetrahydrofuran)-, (T-4)-, polymer with 3-methyl-3-[(2,2,3,3,3-pentafluoropropoxy)methyl]oxetane, ether with 2,2-dimethyl-1,3-propanediol (2:1), bis(hydrogen sulfate), diammonium salt							PFAAs and precursors	Not OECD
477529-30-9	Octadecylacrylat/2-propenoic acid, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,10-heptadecafluorodecyl ester/2-propenoic acid, 3,3,4,4,5,5,6,6,7,7,8,8,9,9,10,10,11,11,12,12,12-heneicosafluorododecyl ester/3-(trimethoxysilyl)propylmethacrylat polymer							Polymeric	8;10

Cas no.	Substance name /Product type code	Product type	No. of products	No. of companies	Prod/Imp max, t PFAS/y	Exp.max, t PFAS/y	Identified max consumption, t PFAS/y	PFAS group	Perfluoroalkyl chain length
1017237-78-3	2-Propenoic acid, 2-[methyl[(1,1,2,2,3,3,4,4,4-nonafluorobutyl)sulfonyl]amino]ethyl ester, telomer with 3-mercapto-1,2-propanediol, 2-methyloxirane polymer with oxirane di-2-propenoate, and 2-methyloxirane polymer with oxirane mono-2-propenoate, tert-Bu 2-ethylhexaneperoxoate-initiated							Polymeric	4
1257095-32-1	Siloxanes and silicones, lauryl Me, Me 2-(2-methylpropoxy)ethyl, Me octyl, Me 3,3,4,4,5,5,6,6,7,7,8,8,8-tetradecafluorooctyl							Polymeric	6
1374418-39-9	2-propenoic acid, reaction products with acetic acid (.ypsilon.-.omega.-perfluoro-c8-10-alkyl)trio derivs. Bu esters and polyethylenimine							Polymeric	6;8
1407491-30-8	Siloxanes and silicones, 3-aminopropyl Me, di-Me, Me 3-mercaptopropyl, polymers with tearyl acrylate, 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl methacrylate, rel-(1R,2R,4R)-1,7,7-trimethylbicyclo[2.2.1]hept-2-yl methacrylate and vinyl chloride							Polymeric	6
Total, unnamed quantities							**8**		
Grand total			**808**	**109**	**128**	**63**	**65**		

Table 111. PFASs maximum import, export and consumption in Danish production by industrial sector in 2023 (Source: The Danish Product Registry; WEA, 2023)

Sector code	Sector of use	CAS no.	Identified substance names		No. of substs	No. of products	No. of companies	Conc min	Conc max	Prod/Imp max (t/y)	Export max (t/y)	Consumption (max-based, t/y)
C162	Manufacture of goods of wood, straw and braiding materials			**Total**	6	23	4	0.0100	50	0.8163	0.816	0.599
C181	Printing and associated services			**Total**	8	90	5	0.0004	5	0.1889	0.189	0.002
		9002-84-0	*Tetrafluorethen polymer*									
C200	Production of chemicals			**Total**	4	4	3	0.0021	70	0.0275	0.028	0.017
C203	Production of paints, varnishes, coatings, inks and sealants		**Total**		8	10	5	0.0010	90	4.2228	4.223	0.000
C256	Surface treatment of metals, machine processing		**Total**		9	287	11	0.0007	95	1.5303	1.530	0.016

Sector code	Sector of use	CAS no.	Identified substance names		No. of substs	No. of products	No. of compa-nies	Conc min	Conc max	Prod/Imp max (t/y)	Export max (t/y)	Consumption (max-based, t/y)
		647-42-7	*1-octanol, 3,3,4,4,5,5,6,6,7,7,8,8,8-tride-cafluoro-*									
		9002-84-0	*Tetrafluorethen polymer*									
		115340-95-9	*Siloxanes and silicones, dimethyl, methyl 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl*									
C259	Manufacture of other finalised metal products			**Total**	1	22	3	0.0040	10	5.6424	5.642	0.000
		9002-84-0	*Tetrafluorethen polymer*									
C261	Production of electronic components, printed circuit boards (PCBs), etc.			**Total**	4	4	4	0.0015	99	0.1089	0.109	0.001
C270	Manufacture of electrical equipment			**Total**	3	4	3	0.0020	100	1.0269	1.027	0.003
C280	Manufacture of machines and equip-ment, not specified elsewhere			**Total**	2	5	5	0.0500	20	0.018	0.000	0.02
		9002-84-0	*Tetrafluorethen polymer*									
C281	Manufacture of machines for general purposes			**Total**	3	6	6	0.0652	100	4.557	3.224	1
		9002-84-0	*Tetrafluorethen polymer*									
C282	Manufacture of other machines for gen-eral purposes			**Total**	5	15	5	0.1200	100	38.165	19.208	19
C301	Construction of ships and boats			**Total**	8	11	6	0.0007	44	0.015	0.016	-0.001
		115340-95-9	Siloxanes and silicones, dimethyl, methyl 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl									

Sector code	Sector of use	CAS no.	Identified substance names		No. of substs	No. of products	No. of compa-nies	Conc min	Conc max	Prod/Imp max (t/y)	Export max (t/y)	Consumption (max-based, t/y)
C310	Manufacture of furniture			**Total**	3	32	5	0.0004	100	3.651	0.996	3
		9002-84-0	*Tetrafluorethen polymer*									
C329	Other manufacturing, not specified elsewhere			**Total**	5	5	3	0.0070	5.2	0.042	0.000	0.04
C331	Repair of iron and metal goods, machines and equipment			**Total**	3	180	6	0.0003	5	0.038	0.002	0.04
		9002-84-0	*Tetrafluorethen polymer*									
F412	Construction of buildings			**Total**	5	12	4	0.0020	0.5	0.046	0.002	0.04
F430	Specialised building and construction			**Total**	5	5	3	0.0007	0.3	0.017	0.000	0.02
F432	Electrical installation, plumbing and other building installation activity			**Total**	3	9	5	0.0135	100	2.529	1.449	1
		9002-84-0	*Tetrafluorethen polymer*									
F433	Completion of buildings			**Total**	9	128	15	0.0003	2.5	0.252	0.028	0.2
		9002-84-0	*Tetrafluorethen polymer*									
		65530-70-3	*Poly(difluoromethylene), a,a'-(phosphinicobis(oxy-2,1-ethanediyl))bis(.omega.-fluoro- ,ammonium salt*									
		65530-71-4	*Poly(difluromethylene), .alpha-fluoro-.omega.-(2-(phosphonooxy)ethyl)-,monoammonium salt*									
		65530-72-5	*Poly(difluoromethylene), .alpha.-fluoro-.omega.-(2-(phosphonooxy)ethyl)-, diammonium salt*									

Sector code	Sector of use	CAS no.	Identified substance names	No. of substs	No. of products	No. of compa-nies	Conc min	Conc max	Prod/Imp max (t/y)	Export max (t/y)	Consumption (max-based, t/y)
		115340-95-9	*Siloxanes and silicones, dimethyl, methyl 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl*								
F439	Other specialised building and con-struction		**Total**	5	4	4	0.0021	2.7	0.031	0.003	0.03
G452	Maintenance and repair of motor vehi-cles		**Total**	16	92	24	0.0002	100	14.534	2.003	13,0
		811-97-2	*1,1,1,2-tetrafluorethan*								
		9002-84-0	*Tetrafluorethen polymer*								
G467	Other specialised gross trade		**Total**	8	43	10	0.0001	7	0.469	0.267	0.2
		9002-84-0	*Tetrafluorethen polymer*								
N812	Cleaning		**Total**	8	9	6	0.0018	2	0.005	0.000	0.005
T980	Consumers' manufacture of goods and services for own use, not specified elsewhere		**Total**	8	13	5	0.0003	2.7	0.024	0.012	0.01
T982	Consumers' manufacture of services for own use, not specified elsewhere		**Total**	6	27	4	0.0004	0.08	0.063	0.012	0.1
		115340-95-9	*Siloxanes and silicones, dimethyl, methyl 3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctyl*								
			Grand total	**70**	**811**	**109**			**127.8**	**63.2**	**64.6**

Appendix 4. Data on import, export and production from Statistics Denmark

Net import of PFAS or products containing PFASs as extracted from Statistics Denmark (statistics UVH3) is shown in the table below. The commodity codes include those specifically indicating that the commodity includes a PFAS or fluoropolymer.

The main reported PFOS related substances in 2022 were n-methylperfluorooctane sulphonamide (CAS No 31506-32-8), tetraethylammonium perfluorooctane sulphonate (CAS No 56773-42-3) and diethanolammonium perfluorooctane sulphonate (CAS No 70225-14-8). In the REACH registration database on ECHA's website, tetraethylammonium perfluorooctane sulphonate substances are registered as "ceased manufacture" with no volumes. In the PFAS Restiction proposal, the registered tonnage band for the substance is indicated at 0-10 t/y (ECHA, 2023). The other two substances are preregistered under REACH but not registered.

Table 112. Net import of PFASs or products containing PFASs. Quantities rounded to one decimal.

		Net import, t/y				
CN 8 code		2018	2019	2020	2021	2022
2904 3100	Perfluorooctane sulphonic acid	0.0	0.0	0.0	0.0	0.0
2904 3200	Ammonium perfluorooctane sulphonate	0.0	0.0	0.0	0.0	0.0
2904 3300	Lithium perfluorooctane sulphonate	0.0	0.0	0.0	0.0	0.0
2904 3400	Potassium perfluorooctane sulphonate	0.0	0.0	0.0	0.0	0.0
2904 3500	Other salts of perfluorooctane sulphonic acid	0.0	0.0	0.0	0.0	0.0
2904 3600	Perfluorooctane sulphonyl fluoride	0.0	0.0	0.0	45.5	0.0
2922 1600	Diethanolammonium perfluorooctane sulphonate	0.2	0.2	0.4	0.5	0.1
2923 3000	Tetraethylammonium perfluorooctane sulphonate	11.6	2.0	1.6	1.6	2.5
2923 4000	Didecyldimethylammonium perfluorooctane sulphonate	0.0	0.0	0.0	0.0	0.0
2931 5300	O-(3-chloropropyl) O-[4-nitro-3-(trifluoromethyl)phenyl] methylphosphonothionate	0.0	0.0	0.0	0.0	0.0
2935 1000	N-Methylperfluorooctane sulphonamide	11.1	22.5	11.8	0.0	26.4
2935 2000	N-Ethylperfluorooctane sulphonamide	0.0	0.0	0.0	0.0	0.0
2935 3000	N-Ethyl-N-(2-hydroxyethyl) perfluorooctane sulphonamide	0.0	0.0	0.0	0.0	0.0
2935 4000	N-(2-Hydroxyethyl)-N-methylperfluorooctane sulphonamide	0.0	0.0	0.0	0.0	0.0
2935 5000	Other perfluorooctane sulphonamides	1.4	1.4	0.0	0.0	0.0
3824 8700	Containing perfluorooctane sulphonic acid, its salts, perfluorooctane sulphonamides, or perfluorooctane sulphonyl fluoride	0.0	10.0	0.0	0.0	0.8
3904	Polymers of vinyl chloride or of other halogenated olefins, in primary forms:					
3904 6100	Polytetrafluoroethylene	1340.1	1084.8	750.6	1030.2	888.2
3904 6900	Other fluoropolymers	0.0	0.0	0.0	0.0	0.0

		Net import, t/y				
CN 8 code		2018	2019	2020	2021	2022
3904 6920	Fluoroelastomers	24.7	35.1	25.5	22.3	27.3
3920 9953	Ion-exchange membranes of fluorinated plastic material, for use in chlor-alkali electrolytic cells	0.3	0.2	0.3	0.0	0.0
8419 5020	Heat exchange units made of fluoropolymers and with inlet and outlet tube bores with inside diameters measuring 3 cm or less	42.8	129.9	93.2	-70.8	-65.7
8421 2920	Filtering or purifying machinery and apparatus for liquids:- Made of fluoropolymers and with filter or purifier membrane thickness not exceeding 140 microns	128.7	169.6	151.2	102.4	218.2

The registered import of four specific PFAS related substances is surprising, considering the use of the substances has been restricted in the EU for a number of years. As shown in the table below, two of the substances are not registered (but are preregistered) under REACH, whereas the other two are registered. However, it is indicated in the registered substances factsheets under “total tonnage band” that manufacture has ceased. Data from the SPIN database along with data from the Product Registries in the Nordic Countries indicate that three of the substances have formerly been used in the countries but that the quantities are confidential.

Table 113. Supporting information for the four specific substances indicated as imported

	CAS No	SPIN (data for all four countries)	REACH registering
Perfluorooctane sulphonyl fluoride	307-35-7	No data	Registered - indicated as “Cease manufacture” and no volume
Diethanolammonium perfluorooctane sulphonate	70225-14-8	Conf. data until 2012	Not registered
Tetraethylammonium perfluorooctane sulphonate	56773-42-3	Conf. data until 2021	Registered - indicated as “Cease manufacture” and no volume
N-Methylperfluorooctane sulphonamide	31506-32-8	Conf. data until 2003	Not registered

In a study on alternatives to PFOS related substances used for hard chrome plating in Denmark (Poulsen et. al., 2011), it is indicated that tetraethylammonium perfluorooctane sulphonate (CAS No 56773-42-3) was formerly the most used substance in the hard chrome plating industry, in the form of the product Fluortensid-248. The main alternative was indicated as Fumetrol® 21 and other brand names, with CAS No 27619-97-2 (3,3,4,4,5,5,6,6,7,7,8,8,8-tridecafluorooctanesulphonic acid, 2:6 FTS) as the active substance. This substance is registered under REACH with a volume in the 10-100 t/y range. In the SPIN database, consumption in Denmark in 2021 is indicated as “confidential”. In a study on the use of PFAS in Denmark, for 2016, a total of 0.18 t/y was registered in the Danish Product Registry (Nicolaisen and Tsitonaki, 2016). The quantity is higher than the quantity of PFAS used for hard chrome plating, which is indicated at 10-28 kg/year of the pure substances in Poulsen et al. (2011).

A likely explanation for registration of tetraethylammonium perfluorooctane sulphonate could be that the importer historically used this commodity code and still uses it in the absence of other specific codes for the PFAS in question. As concerns the large quantities (as compared to the quantities reported to the Product Registry), the explanation may be that the commodity

registered under commodity code 2923 3000 is a mixture with a low content of the PFAS active substances. For Fumetrol® 21, Poulsen et al. (2011) indicated a content of CAS No 27619-97-2 at 1-2.5% (w/w). If a similar concentration is assumed for the mixtures imported to Denmark today, the approximately 2 t/y registered for commodity code 2923 3000 would correspond to 0.02 to 0.05 t/y active substance, which is close to the data registered in the Danish Product Registry and reported to be used for the purpose.

The 45.5 t/y reported for perfluorooctane sulphonyl fluoride in 2021 appears to be a classic mix up of commodity codes, as no import of N-methylperfluorooctane sulphonamide is registered for this year.

For N-methylperfluorooctane sulphonamide and diethanolammonium perfluorooctane sulphonate, no likely explanation for the registered quantities has been identified. For N-methylperfluorooctane sulphonamide, import has been registered from France, Poland, Sweden, and Czeck Republic (from up to 3 countries some years) during the period 2018-2022, indicating it is not a single erroneous reporting. According to Nicolajsen and Tsitonaki (2016), no data are reported to the Danish Product Registry for this substance. Production is reported for three commodity codes only in the production statistics (Statistics VARER1) of Statistics Denmark, shown in the table below. The data on quantities were available for commodity code 84195020 only, whereas for the other two commodity codes, quantities are estimated from the value of the production in DKK and the t/DKK reported for exported products. This estimation method is highly uncertain.

Table 114. Reported production of PFAS or products containing PFAS

		Production, t/y				
CN 8 code		**2018**	**2019**	**2020**	**2021**	**2022**
39046100	Polytetrafluoroethylene	61.6	87.0	79.9	91.3	0.0
84195020	Heat exchange units made of fluoropolymers and with inlet and outlet tube bores with inside diameters measuring 3 cm or less	18.7	50.0	42.4	30.6	51.9
84212920	Filtering or purifying machinery and apparatus for liquids:- Made of fluoropolymers and with filter or purifier membrane thickness not exceeding 140 microns	61.2	31.5	28.4	0.0	0.0

Appendix 5. PFASs in discharges from point sources other than sewage treatment plants

COWI has received data from the Danish EPA with 75 point sources with direct discharges to surface water. The dataset consists of 1,058 datapoints along with measurement of PFASs from 18 point sources. For the remaining 57 sources, no PFAS data are available.

All results below LOD were calculated as a concentration of half the LOD. No results were excluded as the lowest detection limit was 10 nanograms per liter.

The average concentration of the different PFASs are shown in Table 115.

Four of the sources stand out with concentrations well above the average concentration of effluent from sewage treatment plants: Fire school, landfill for sewage sludge, a disposal facility/engineered landfill and a centre for storage and pretreatment of residues from MSWI.

The average reported ∑16 PFAS concentration in leachate from the eight different landfills was 131 ng/L, which is far below the reported average $PFAS_{22}$ concentration in leachate from engineered landfills discharged to municipal sewage treatment plants of 3,300 ng/L (see Table 84). However, the discharges are not completely similar as the discharges from the landfills are mainly to surface water or groundwater or leachate from landfilled marine sediments.

The total discharge of ∑16 PFAS can be estimated at 1.3 kg/y, of which one facility accounts for 94%. Total discharge of PFAS4 can be estimated at 0.05 kg/y; the relatively small quantity reflects that $PFAS_4$ only accounts for a small fraction of the discharges from the main source.

Table 115. Average concentrations measured PFASs in effluent from Danish sources with direct discharge to surface water, years 2020-2023. All figures in ng/L.

Sub-stance	Chain length	Airport	Fire school	Eng. Landfill, surface water	Eng. Landfill, surface water	Landfill for sedi-ment	Eng. Landfill	Eng. Landfill, surface water	Eng. Landfill, grund-water	Landfill - Harbour sediment	Landfill - special sludge	MSW! process water	MSWI flue gas conden-sation	MSWI flue gas conden-sation	MSWI flue gas cleaning	MSWI waste water	Disposal facility	Industrial surface water
PFBS	C4	0.5	0.9	4.1	5.6	0.5	5.5	0.8	0.2	1.0	25.0	2.0	0.3	0.2	0.2	21.5	21.5	5.0
PFBA	C4	0.5	12.8	7.3	6.9	0.5	10.0	1.7	0.3	15.0	38.0	31.7	0.4	0.3	4.5	120.4	120.4	5.0
PFPeS	C5	n.d	0.7	0.6	0.2	n.d	4.5	0.2	0.2	n.d	3.6	0.2	0.2	0.2	0.2		n.d	5.0
PFPeA	C5	1.3	40.2	6.2	2.1	3.1	9.2	0.5	0.3	3.0	89.7	45.3	0.3	0.2	1.6	892.9	892.9	5.0
PFHxS	C6	0.8	4.1	0.8	0.5	0.5	25.0	0.2	0.2	1.0	10.7	1.0	0.3	0.2	0.2	4.5	4.5	5.0
PFHxA	C6	1.2	27.1	7.6	2.0	2.8	15.0	0.8	0.6	3.0	61.7	60.7	0.3	0.2	1.0	642.8	642.8	5.0
PFHpS	C7	n.d	0.7	n.d	0.2	n.d	3.9	0.2	0.2	n.d	0.3	0.2	0.2	0.2	0.2		n.d	5.0
PFHpA	C7	0.8	12.7	3.4	1.4	6.3	17.0	0.5	0.3	2.0	56.0	0.7	0.3	0.2	0.2	103.3	103.3	5.0
PFOS	C8	0.4	21.3	3.3	21.0	0.7	77.0	1.1	0.2	2.0	16.7	0.4	0.3	0.5	0.1	11.2	11.2	2.5
PFOA	C8	0.5	7.0	6.0	2.9	11.1	100.0	1.4	0.6	4.0	102.0	0.7	0.3	0.2	0.2	1.9	1.9	2.5
PFNA	C9	0.5	2.5	0.6	0.5	0.5	5.0	0.2	0.2	0.5	1.9	0.4	0.3	0.2	0.2	0.7	0.7	5.0
PFDS	C10	n.d	0.5	n.d	0.5	n.d	0.2	0.2	0.2	0.5	0.2	0.5	0.5	0.2	0.2		n.d	5.0
PFDA	C10	0.5	6.8	n.d	0.4	0.5	0.2	0.2	0.2	0.5	0.3	0.4	0.3	0.2	0.2	0.6	0.6	5.0
PFUnDA	C11	0.5	0.8	n.d	0.5	n.d	0.2	0.2	0.2	n.d	0.2	0.5	0.5	0.2	0.2		n.d	5.0
PFDoDA	C12	n.d	0.6	n.d	0.5	n.d	0.2	0.2	0.2	n.d	0.2	0.5	0.5	0.2	0.2		n.d	5.0
PFTrDA	C13	n.d	0.9	n.d	0.5	n.d	0.5	0.5	0.5	n.d	0.5	0.5	0.5	0.5	0.5		n.d	5.0
$PFAS_4$		2.2	34.8	10.7	24.9	12.8	207.0	2.8	1.2	7.5	131.3	2.4	1.3	1.0	0.6	1.3	18.3	18.3
∑16 PFAS		7.1	139.5	39.9	45.6	26.4	273.2	8.5	4.2	32.5	406.8	145.4	5.6	3.3	9.3	7.5	1799.7	75.0
Flow m^3/year		195,538	n.d.	4,957	485	35,597	102,240	5,891	260,457	7,397	87,515	51,587	76,958	26,505	26,505	38,692	696,647	118,907
Total discharge, kg/y		0.001	-	0.0002	0.00002	0.0009	0.0279	0.0001	0.0011	0.0002	0.04	0.008	0.0004	0.0001	0.0001	0.0003	1.254	0.009

n.d.: not determined.

[Bagside Overskrift]
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