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Parameterized Data Model for Enhanced PFAS-Emission Calculations Based on Public European Data

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Keywords

Data Model, ECHA, Emissions, Fluoropolymers, PFAS 13 14

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1. Introduction

In 2023, five European countries submitted a proposal to ECHA to restrict the manufacture, use, and placing on the market of per- and polyfluoroalkyl substances (PFAS) [1]. This PFAS dossier identified 14 application sectors plus separately the manufacture of raw material. The dossier submitters updated and extended the original dossier in an iterative way and published its 14th version as Background Document (BD) with eight additional application sectors [2]. As part of the formal legislative process ECHA's scientific risk assessment committee (RAC) published its formal opinion on the dossier earlier this year [3] which evaluates the scope of the original dossier, not the eight additional sectors.

RAC notes especially regarding FP that the whole lifecycle needs to be considered. It points further out that the proposed OECD policy criteria for "polymers of low concern" only include the end-use [and service life] (U&S) of polymers, making it an incomplete assessment which dismisses all other life cycle stages like raw material production (RAW), product manufacturing (PROD), end-of-life (EoL). A more comprehensive view and an analysis of dependencies on factors that might influence emissions would be desirable. Such details would put the legislator in the driver's seat and provide them with a cockpit to distinguish major from minor emissions and to differentiate between emissions from FP and other PFAS as well as emissions along the life cycle.

1 Interestingly, the detailed data provided by the scientific committee itself would allow to distill these
2 valuable details as well as the overall emissions originating from FPs and appreciating their share
3 amongst all PFAS emissions. If there is a significant difference to the previous status of knowledge
4 which is based on the BD from 2025 this needs to be included in further considerations. With the
5 information presented by RAC earlier this year these open questions are not satisfactory answered.

6 PFAS are considered an extensive heterogenous group of molecules that contain at least one fully
7 fluorinated methyl (-CF₃) or methylene- (-CF₂-) carbon atom to which no hydrogen or other halogen is
8 bonded. Based on the PFAS classification scheme shown in Figure A.2. of Ref. [2], ECHA uses three
9 main PFAS groups for the impact assessment:

- 10 – Perfluoroalkyl acids and their precursors, including side-chain fluorinated polymers (“PRE”)
- 11 – Fluorinated gases (“GAS”)
- 12 – Polymeric PFASs: fluoropolymers (“FP”) and perfluoropolyethers (“PFPE”)

13 Substances not falling within these main groups are considered “other PFAS” like -CF₃ on
14 pharmaceuticals or other active substances.

16 2. Methodology

17 2.1. Baseline Emissions for FP

18 Within ECHA’s framework PFAS emissions are regarded as proxy for risk. A more granular analysis of
19 the current RAC data requires to set a baseline how emissions were distributed according to the BD in
20 2025. From Table 1 of Ref [2] we only consider the original 14 plus one (14+1) sectors, leaving the
21 eight new sectors aside because RAC does not publish corresponding data. In the BD GAS represents
22 the PFAS-group with the most emissions (46,195 t/a, 67.5%), followed by polymeric PFAS (15,129 t/a,
23 22.1%) and PRE (7,153 t/a 10.5%) with total emissions of 68,447 t/a which closely matches RAC’s
24 total PFAS emissions. So, emissions from polymeric PFAS, which combine emissions from FP and
25 PFPE, can be regarded as a relevant share of all PFAS emissions. The BD does not detail FP or PFPE
26 emissions. We later understand from our data model (Table 2) that PFPE contribute 937 t/a when
27 reconstructing from RAC’s data the status of the BD. Subtracting that from polymeric PFAS emissions
28 yields 14,192 t/a for FP emissions as the previous status of knowledge. This annual tonnage is used as
29 2025 baseline for FP emissions.

30 2.2. Data Reconstruction

31 Each sector specific RAC opinion has been analyzed regarding their very detailed information about
32 emission contributions and pathways, in particular PFAS raw material manufacturing [4], textiles,
33 upholstery, leather, apparel and carpets products (TULAC) [5], application of fluorinated gases [6],
34 medical devices [7], transport [8], lubricants [9], food contact materials and packaging (FCM) [10],
35 construction products [11], electronics and semiconductors [12]. The six sectors with the lowest PFAS
36 emissions [3] have been omitted in our analysis, namely the use sectors metal plating, consumer
37 mixtures, cosmetics, ski wax, energy and petroleum & mining. The eight additional sectors identified
38 by the dossier authors could not be considered in our analysis since RAC does not provide data for
39 these omitted sectors which are: printing applications, sealing applications, machinery applications,

other medical applications, military applications, explosives, technical textiles and broader industrial uses [3].

2.2.1. Structure of RAC Datasets

Starting point in RAC's calculation is an annual tonnage of a certain PFAS fraction specific to a use sector (i), sub-use (j), life cycle phase (k) and PFAS subgroup (l). RAC refers to the annual tonnage as "PFAS volume". There are 14 +1 referenced use-sectors, a manifold of sub-uses, the four mentioned life cycle stages and four PFAS subgroups: PRE, GAS, FP and PFPE. Interestingly, all sectors specific opinions allow to differentiate between FP and PFPE which together are polymeric PFAS.

PFAS emissions (E) are considered linearly proportionate by RAC to the PFAS volume (V) with the factors r, f, p differently depending on i, j, k, l:

$$E_{i,j,k,l} = r_{j,k} \cdot f_{k,l} \cdot p_{j,k} \cdot V_{i,j,k,l} \quad (1)$$

The **release factor (r)** is adopted from the dossier submitters.

–If there is specific information like for EoL, those values for this r- value are considered (e.g. incineration 0.02, hazardous waste incineration 0.01, landfill 0.0336)

–In rare cases where there is specific information, only a fixed emission value is mentioned precluding insights into underlying dependencies and preventing later parameterization. E.g. for electronics and semiconductors, fluorinated gases, U&S in transport or wastewater in construction.

–In cases where specific information is lacking generic environmental release categories (ERC), ranging from ERC1 to ERC 12c, described by ECHA elsewhere [13, App. R.16-1], are applied.

The **f-factor** is newly introduced by RAC and described in chapter 3.1.2.4. Emissions from fluoropolymers in Ref. [3]. RAC describes its "alternative approach for estimating emissions from the use stage and landfilling of fluoropolymers. In that approach, the RFs proposed by the dossier submitters are applied only to the non-polymeric fraction, which has been, for the purpose of emission estimation, set by RAC at 0.1%." This factor is called f-factor in this publication. RAC refers to OECD (Organization for Economic Co-operation and Development) on plastic additives 2009 [14], applying e.g. the situation of plasticizers in polyvinyl chloride (PVC) to FP. It should be mentioned that this factor is applied to FP as well in the life cycle stage PROD. This is not mentioned by RAC in the text but consistently applied to all corresponding data. For landfilling FP, RAC mentions a combined release factor (0.0000336) which is 0.001 (f-factor) multiplied by the genuine landfill release factor (0.0336). This is important to differentiate if it is about later parameterization.

$$f = \begin{cases} 1 & \text{for } l: \text{PRE, GAS, PFPE} \\ 0.001 & \text{for } l: \text{FP, } k: \text{PROD, U\&S, Landfill} \\ 1 & \text{for } l: \text{FP, } k: \text{Incineration} \end{cases}$$

The **percentage (p)** being assigned to a pathway e.g. for EoL being split into different fractions. If there is no value presented, p=1. Different pathways m within one data segment are already summed up

$$E_{i,j,k,l} = \sum_m r_{j,k} \cdot f_l \cdot p_{j,k,m} \cdot V_{i,j,k,l} \quad (2)$$

An example of such raw data for the medical device sector is shown in Table 1.

Table 1: A simplified excerpt of table 2 in RAC's opinion for medical devices (use sector), non-invasive/non-implantable medical devices (sub-use). Only mid-values (M) are shown. The original data provides low and high estimates as well. When parameterizing the data in a later step, the set values for the f-factor, for incineration or landfill are replaced by adjustable parameters. Only a selected segment of the total emissions from medical devices is shown, representing 118 out of 127 t/a.

Application		PFAS Volumes (t/a)	Release Factor (RF)	PFAS Emissions (t/a)
[sub-] use	Life cycle stage	FP	Compartment / waste treatment	
Non-invasive/non-implantable medical devices	PROD	M: 7 578	ERC 5 0.5 <i>A factor of 0.001 applied to estimate non-polymeric emissions from fluoropolymers</i>	M: 3.8
	EoL	M: 7 578	54.9% incineration as non-hazardous waste (0.02); 41.4% incineration as hazardous waste (0.01) 3.7% landfill (0.0000336)	M: 114.4

The information is detailed and allows to allocate the use-sector (i: medical device), sub-use (j: as specified), life cycle stages (k: PROD, EoL), PFAS subgroup (l: FP) and information about release factors (RF). The right column shows PFAS emissions.

2.2.2. Bottom-up Reconstruction of the Data Model

Having the structure analyzed we now can reconstruct the presented emission value in Table 1 as follows:

The first row yields with (1) an exact match with 3.8 t/a

$$E_{i,j,k,l} = 0.5 \cdot 0.001 \cdot 1 \cdot 7,578 \frac{t}{a}$$

The second row with three different pathways for EoL requires (2)

$$E_{i,j,k,l} = (0.02 \cdot 1 \cdot 0.549 + 0.01 \cdot 1 \cdot 0.414 + 0.0036 \cdot 0.001 \cdot 0.037) \cdot 7,578 \frac{t}{a}$$

which yields with 114.58 t/a a close but not an identical match, it deviates by +0.2% from 114.4 t/a. We consider the first row as one data point, the second as 3 data points (due to the 3 summands) for bookkeeping.

This is continued with all specific sub-uses in medical devices as use category and aggregated over all sub-uses (j) so that emissions can be calculated being specific for use-sector (i), life cycle phase (k) and PFAS subgroup (l).

$$E_{i,k,l} = \sum_j r_{j,k} \cdot f_{k,l} \cdot p_{j,k} \cdot V_{i,j,k,l} \quad (3)$$

This results in emission values for medical devices (i), originating from fluoropolymers (l) and being split by life cycle phase (k): PROD (3.8t/a), U&S (0.01 t/a) and EoL (123.6 t/a).

With

$$E_{i,l} = \sum_k E_{i,k,l} \quad (4)$$

127.4 t/a for FP in medical devices is achieved (supporting information) deviating +0.3% from the 127 t/a reported by RAC. The chosen example is simple because it only reports emissions originating from FP. All other use sectors exempt [6] have multiple PFAS subgroups to be considered.

RAC provides only information after an additional aggregation not distinguishing between PFAS subgroups which is reported in its table 5 in Ref. [3].

$$E_i = \sum_l E_{i,l} \quad (5)$$

Aggregated values for PFAS subgroups can be achieved with

$$E_l = \sum_i E_{i,l} \quad (6)$$

RAC also provides overall PFAS emissions according to

$$E = \sum_i E_i \quad (7)$$

Using our subtotals (3) allows enormous granularity on the aggregated levels. These bottom-up calculations are slightly simplified, using RAC's mid value (M). In its original data set, RAC additionally uses Lower (L) and higher (H) estimates.

2.3. The Reconstructed Data Model

Calculation (3) is repeated for all data points in the eight biggest use sectors plus emissions from RAW which is considered separately by RAC, further referred to as 8+1. Data points smaller than 0.5 t/a are disregarded in 53 cases. A total of 270 data points out of 323 are reconstructed bottom up. The corresponding data is available as supporting information. The results are shown in Table 2.

- 1 Table 2: Data model based on data from RAC sector specific opinions showing detailed values
- 2 according to (3). Focusing on FP the main emissions come from raw material manufacture and from
- 3 EoL. Only values smaller than 10 are shown to one decimal place. Empty cells stand for no
- 4 contribution or values smaller 0.05.

Life cycle stage		PFAS subgroup emissions t/a			
		PRE	GAS	FP	PFPE
RAW					
	RAW	473	51	221	
	S&U				
	EoL	8.6	0.8	6.3	
TULAC					
	PROD	932		3.9	37
	U&S	4,620		1.2	71
	EoL	316		537	18
FCM					
	PROD	394		0.1	
	U&S	8.0			
	EoL	53		137	
Applications of fluorinated gases					
	PROD				
	U&S		32,227		
	EoL		7,119		
Medical Devices					
	PROD			3.8	
	U&S				
	EoL			124	
Transport					
	PROD		29		
	U&S	0.4	15,330	0.5	
	EoL	0.3	3,553	213	
Electronics					
	PROD	11	3.6		83
	U&S		242	10	1.9
	EoL	19	45	11	12
Construction					
	PROD	22		0.2	
	U&S	194		3.4	
	EoL	101		107	
Lubricants					
	PROD	4.7	0.6	0.2	122
	U&S	21	2.5	0.8	550
	EoL	1.5	0.2	70	40

3. Results

3.1. Verification of the Data Model

The reconstructed data model is verified by comparing aggregated sector totals (5) and total PFAS emissions (7) with the corresponding values reported by RAC [3, Tbl. 5]. This is shown in Table 3.

Table 3: Comparing aggregated use sector totals (5) and total PFAS emissions (7) with the corresponding values reported by RAC [3, Tbl. 5]. Figures from our data model include one decimal, RAC only reports integers. Without that step small deviations as seen in medical devices would result in 0% deviation which is too coarse for a critical comparison.

	PFAS use-sector emissions t/a		Deviation
	RAC data	data model	
RAW	761	760.6	< 0.1%
TULAC	6,526	6,536.3	+ 0.2%
FCM	582	591.7	+ 1.7%
Applications of fluorinated gases	39,346	39,346	0%
Medical Devices	127	127.4	+ 0.3%
Transport	19,106	19,126.1	< 0.1%
Electronics	440	438.8	- 0.3%
Construction	426	426.7	+ 0.2%
Lubricants	815	814.7	< 0.1%
Sum of Emissions E (8+1 sectors)	68,129	68,168.4	0.06%

The data model presented can reconstruct overall emissions E (7) with 68,168 t/a with a minor deviation of < 0.1%. The small overall deviation is based on non-parameterized values in the dominating use sectors applications of fluorinated gases [6] and transport [8]. The biggest sector-based deviation is in FCM, where RAC factor-values do not match (EoL, consumer cookware in [10]) sum values.

There is an additional reference made by RAC [3, p. 80] that GAS is the largest contributor with roughly 60,000 t/a. In the same context total PFAS emissions are referenced as roughly 70,000 t/a. On this coarse level our data model nicely matches with 58,603 t/a for GAS which roughly contributes 86%. The second largest contributor referenced by RAC is PRE, sparing out numerical values. This is an indirect indicator that FPs no longer are in second position as the BD tells and their emissions need to be smaller than 7%. More is not mentioned about the numeric contribution of FP in general by RAC.

With the data and methods available this is regarded as sufficient validation of the data model with respect to RAC's data.

3.2. A Cockpit for Decision Makers

New information is generated for all life cycle stages for PRE, GAS, FP and PFPE:

$$E_{k,l} = \sum_i E_{i,k,l} \quad (8)$$

Emissions from RAW are described in [4] separately and referred to in Table 2. RAC publishes data for RAW emission values for polymeric PFAS as a sum, not separating it into FP and PFPE which is done for the other use sectors. For this data model, it is assumed that all that polymeric PFAS emissions during RAW are attributed to FP avoiding underestimating FP-emissions.

The resulting values from (6) and (8) are shown in Table 4. This representation of data can be considered as a cockpit, the most compact form for decision makers. In later steps this can be adapted by modifying parameters.

Table 4: PFAS emissions $E_{k,l}$ by PFAS subgroup (l) and life cycle stage (k) from the data model based on RAC's original data. *RAC publishes a value for polymeric PFAS, not separately for FP and PFPE. For not underestimating FP-emissions in our data model, the value is completely assigned to FP.

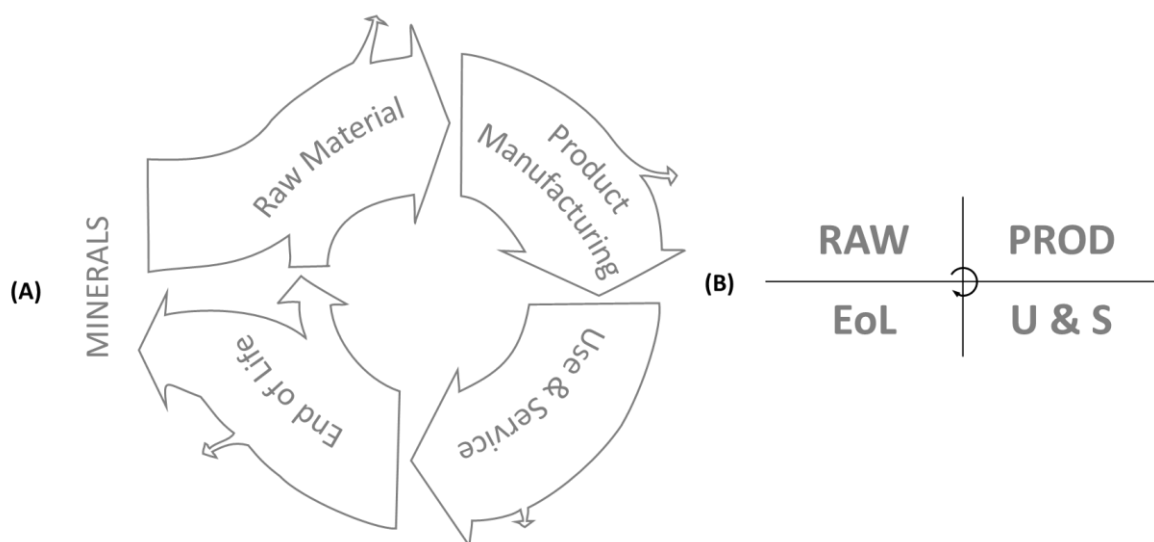
Emissions t/a	PRE	GAS	FP	PFPE
RAW	473	51	221*	-
PROD	1,364	33	8	243
U&S	4,844	47,801	16	623
EoL	500	10,718	1,204	71
Sum	7,180	58,603	1,449	937

Taking all RAC assumptions and parameters into account yields in our data model for GAS 58,603 t/a (86.0%), followed by PRE with 7,180 t/a (10.5%), FP with 1,449 t/a (2.1%) and PFPE with 937 t/a (1.4%). This is in significant contrast to FP-emissions (14,192 t/a) we described as baseline with BD-data.

3.3. Visualization

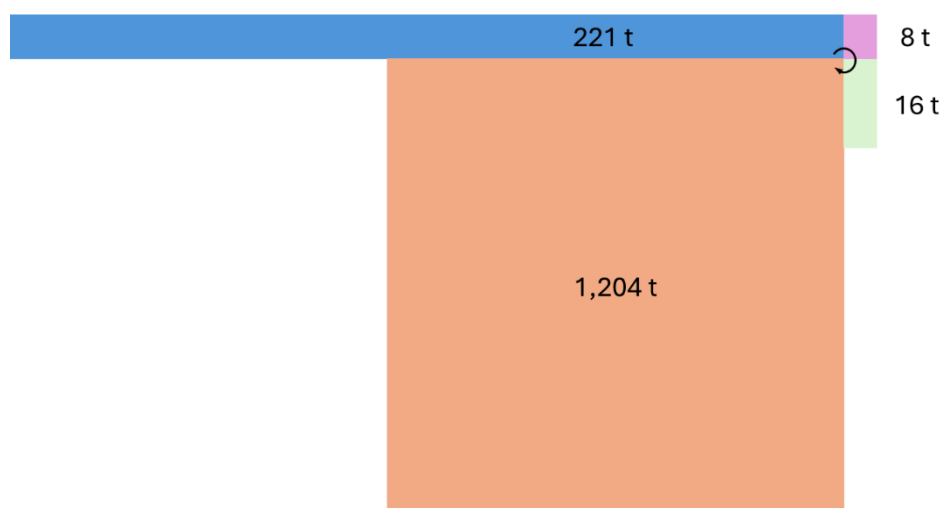
It is important to assess emissions along the different life cycle stages. Figure 1 (A) shows a schematic representation thereof used in its original form in the European's Topic Centre on Waste and Materials in a Green Economy[15]. Maintaining the orientation of these four sectors, a new type of visualization is presented (B) with RAW in the upper left quadrant followed clockwise by the consecutive life cycle sectors.

Figure 1: (A) FP life cycle stages, based on [15], modified. Starting with minerals, PFAS raw material is produced, followed by product manufacturing, use- and service-life. End of life is either landfill or incineration where the main part is transformed into stable minerals. Each stage has emissions; upcycling of FP is still a small pathway not considered here. (B) The arrangement of the four different sectors is transferred to the later visualization scheme of emission volumes centered around a symbol for clockwise order.



The emissions $E_{k,l}$ (8) for the different life cycle stages are represented by rectangles with surface areas proportionate to the emission values. Focusing on FP the values are visualized as in Figure 2. The two-dimensional representation chosen additionally allows to graphically visualize values which are spread over more than 2 orders of magnitude without the use of a logarithmic scale.

Figure 2: Visualization of the emissions resulting from FP from the different life cycle stages according to original RAC data. The four quadrants RAW, PROD, U&S, EoL are arranged as shown in Figure 1. RAW being the top left quadrant, the others follow clockwise. Surface areas are proportionate to the emission values. A total of 1,449 t/a are emitted.



4. Parameterizing the Data Model

The Data model gains additional functionality by modelling the complete data set with parametrizing values for

- f-factor
- r-values for RAW, like for PRE, GAS and polymeric PFAS
- r-values for EoL, like for hazardous and non-hazardous waste incineration or landfill

This means that the fixed values of above-mentioned factors in the simple data model are all replaced by parameters that can globally be adjusted in the parameterized data model. An example is described in Table 1.

For the sector of electronics and semiconductors no reference is made regarding type of waste stage (incineration, landfill, other) [12, pp. 16–23]. For that sector, accounting for 0.6% of PFAS emissions, no dependency regarding different values for RFs during EoL can be modeled.

RAC uses the values for the mentioned parameters shown in Table 5.

Table 5: Parameter values used by RAC including references. For better comparison, values are shown as ppm.

<i>f</i>	1,000 ppm	[3, p. 52]
<i>r</i> (PRE RAW)	5,500 ppm	[4, pp. 13–14]
<i>r</i> (GAS RAW)	6,500 ppm	[4, pp. 13–14]
<i>r</i> (FP RAW)	3,480 ppm	[4, pp. 13–14]
<i>r</i> (landfill)	33,600 ppm	[3, p. 45]
<i>r</i> (incineration)	20,000 ppm	[3, p. 45]
<i>r</i> (Incineration, hazardous)	10,000 ppm	[3, p. 45]

Within the parameterized data model, the influence of changing parameters can be appreciated. We show the influence of certain parameter sets which we label “scenarios” only arguing on a high-level which literature would support such. The model is completely open to showing the influence of any other settings.

Where data as for [6] cannot be parameterized, no dependencies can be modeled. Therefore, GAS which is the biggest contributor, cannot be modeled. Here we will focus on certain settings for FP and PRE.

4.1. Fluoropolymer-specific Considerations

RAC’s opinion shows the most relevant changes for FP. They will be analyzed in some detail also to help us understand where the change comes from.

4.1.1. Influence of the f- Factor as key determinant

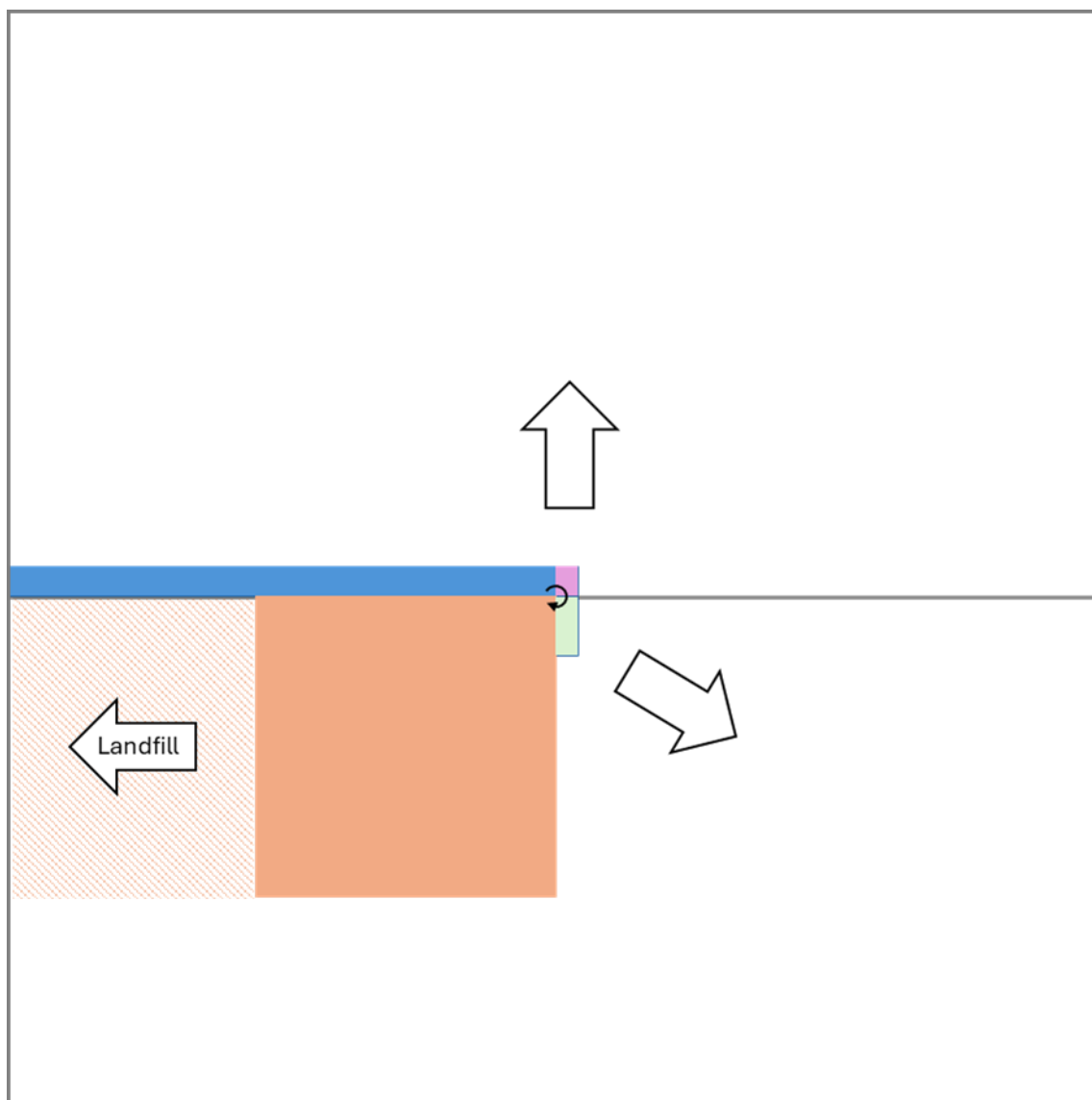
RAC acknowledges in its opinion the excessive overestimation of emissions attributed to fluoropolymers. To adapt this systematic overestimation RAC has introduced its alternative approach

[3, p. 53] with a new overall factor of 0.001 to approximate the non-polymeric emissions from fluoropolymers in PROD, U&S and landfill.

Additionally, FP-particles or microplastics are acknowledged but excluded from RAC's emissions calculation. It further states that they have a different behavior in the environment and different hazard profiles.

At first sight it remains unclear if the significantly reduced emission volume attributed to FP comes from the introduction of this f-factor or from skipping emissions from particles or microplastics. Setting the f-factor back from 0.001 to 1 result in $E_{k,l}(f=1)$ for FP which is visualized in along the life cycle (Figure 3).

Figure 3: RAC data with f-factor reset from 0.001 to 1 resulting in total emissions (big overall square) from FP of 15,966 t/a as a result from the described parameterized data model. For reference: RAW emissions (221 t/a) are unchanged to Figure 2. The sectors are arranged as explained in Figure 1; PROD increasing from 8 to 8,294 t/a, U&S increasing from 16 to 5,287 t/a and EoL increasing from 1,204 to 2,165 t/a solely due to the influence of the f-factor to landfill emissions.



With (6) E_i result in 15,966 t/a of FP-emissions ($f = 1$) which is close to the FP-baseline we assume for the BD to be 14,109 t/a. The difference (+13%) means that RAC considers more sources for FP-based PFAS emissions than BD. They will be weighted less by a factor of 1,000.

Particle or microplastics emissions seem to be a far subordinate factor which unfortunately seems not to be quantified by RAC in an aggregated way. Only the FCM sector specific opinion [10, Tbl. 2] displays emissions of microplastics leaving 247.5 t/a out of the RAC's scope. These 247.5 t/a would add to the 15,966 t/a when we are back projecting to the BD-status.

The introduction of the f -factor by RAC results in a highly significant reduction of the back projected data from 15,966 t/a down to 1,449 t/a (-91%) or from the assumed FP-baseline in the BD down from 14,109 t/a (-90%).

For PROD a straight influence of the f -factor is seen with a reduction of a factor of 1,000, meaning 8,294 t/a go down to 8 t/a. For U&S it is not that obvious at first sight. Here as well the same factor applies. Because values for electronics (10t/a) and transport (1 t/a) presented by RAC cannot be parameterized, 11t do not scale down but remain constant. These 11 t add to 0.001 times (5,287 minus 10t/a) resulting roughly in 16 t/a. RAC qualifies this 16 t/a of emissions as very low [3, p. 57]. Within EoL only landfilling is affected by that factor and reduces landfill-based emissions originating from FP by 962 t/a down to 0.9 t/a. Raw material manufacture is not affected by this parameter as well as incineration.

4.1.2. Influence of RAW Release Factors

RAC assumes r -values for RAW for FP to be 3,480 ppm (Table 5) which refers to emission permits for Chemours in Dordrecht [4, pp. 13–14] dating back to 2019. Industry association Fluoropolymers Group (FPG) of Plastics Europe testified by early 2025 (FPG 2025, [16]), based on measurements, 100 ppm for the European production sites of six different manufacturing companies which we consider within scenario "Conservative". For 2030 FPGs commitment is to achieve 36 ppm (FPG 2030); this might be considered as scenario "Advanced". The dossier authors completely derogate PFAS production if emission limits are considered [2, Pt. derogation 4m] that in a broad way mirrors FPG's proposal.

Applying these different r -values to the volume of FP manufactured within Europe (63,380 t/a) [4, p. 13] reduces emissions from 221 t/a (RAC) to 6 t/a (scenario "Conservative"). Going down to FPG 2030 values (36ppm) yields additional 4 t/a of reduced PFAS emissions (scenario "Advanced"). RAC discusses FPG's initiative extensively [4, pp. 21–26] but refrains from a clear and aggregated comparison of their scenarios in terms of emissions.

4.1.3. Influence of EoL Release Factors for FP

Considering the FP-related PFAS-emissions (1,449t/a) in Table 2 the biggest contributors beside raw material production (221t/a) are: TULAC (537t), transport (213t), FCM (137t), medical devices (124t), construction (107t), lubricants (70t). They are all related to EoL. The dominance of EoL-contributions is also visible in Figure 2. Table 6 shows how r -values can significantly reduce PFAS emission volume.

Table 6: EoL emissions originating from FP. All volume values contain the fraction attributed to landfill with 0.9 t/a. The scenario “Conservative” is supported by [17], [18], the scenario “Advanced” by [19], [20]. Even lower r-values are supported by [21], [22] (99.999%) or [18] (99.9999999%). Gehrmann et.al. already demonstrated 2024 [19] that there is no relevant gain in mineralization rate increasing temperatures from 860°C to 1095°C.

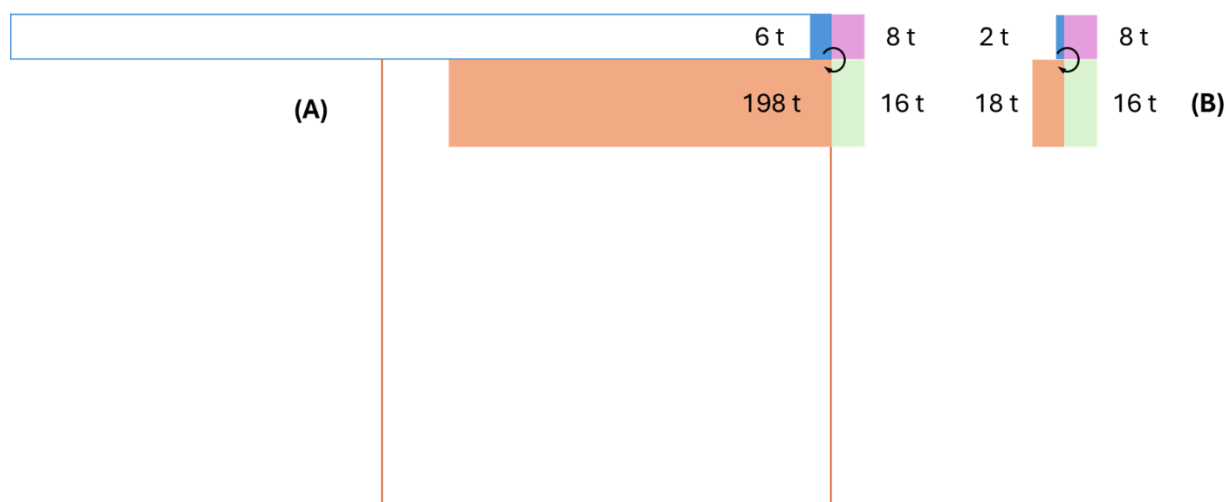
Scenario	Mineralization rate (1-r)	r-value	Emission volume t/a
RAC	98.0% (municipal) 99.0% (hazardous)	20,000 ppm 10,000 ppm	1,204
Scenario “Conservative”	99.7%	3,000 ppm	198
Scenario “Advanced”	99.99%	100 ppm	18

By purely considering r-values, incineration is the most effective way of PFAS destruction, if $r < 33.6$ ppm for incineration (mineralization rate higher than 99.997%), with $r=33.6$ ppm for landfilling fluoropolymers as a benchmark (Table 5).

4.1.4. Visualizing Emission Scenarios for FP

The influence of r-values for raw material manufacturing and incineration can be visualized. The *f-factor* remains unchanged (0.001) as well as r-values for landfill (3.36%). Emissions during PROD and U&S are affected by the *f-factor* and do not change when it is unchanged. The scenarios coined as “Conservative” and “Advanced” for RAW and EoL (Table 6) are combined and visualized in Figure 4. In these scenarios the contribution of FP-related PFAS-emissions go down to 0.34% or 0.07% respectively.

Figure 4: Visualization of the combined scenarios “Conservative” (A) and “Advanced” (B). The four quadrants RAW, PROD, U&S, EoL are arranged as shown in Figure 1. The surface areas are proportionate to the emission values. (A) uses $r=100$ ppm for RAW and 3,000 ppm for incineration. A total of 228 t/a are emitted, which equals 0.34% of all PFAS emissions. The blank rectangles in (A) depict emissions as used by RAC’s original parameters, 3,480 ppm for RAW, 20,000 ppm for incineration and 10,000 ppm for hazardous waste incineration with a total of 1,449 t/a (2.1%) of all PFAS emissions. (B) uses 36 ppm (RAW) and 100 ppm (incineration) respectively and results in 44 t/a (0.07%) of all PFAS emissions.



4.2. PRE-specific Considerations

Additionally, we only highlight the subgroup of PRE which stands for 7,180 t/a of all PFAS- emissions (Table 4). There, main emissions come from PROD and U&S. RAC’s raw data provide more granular insight, which has not been shown previously. For PRE we abstain from providing visualizations.

4.2.1. PRE-Emissions during RAW

RAC sets the r -value for RAW at 5,500 ppm [4]. For the sake of appreciating the emissions-reduction potential of derogation 4m (BD, 36 ppm in 2030), emissions could go down from 473 t/a to 3 t/a. This is in contrast to the depicted scenarios for FP a projection to the future.

4.2.2. PRE-Emissions during PROD and U&S

Emissions during PROD (1,364 t/a) are dominated by TULAC formulation of mixtures (619 t/a), manufacture of paper and board packaging (394 t/a) and TULAC article production (312 t/a). Emissions from U&S (4,844 t/a) are dominated by consumer apparel (3,400 t/a), treatment of textiles with mixtures (930 t/a), professional apparel and PPE (300 t/a). This information is generated by checking the individual contributions ([supporting information](#)).

4.2.3. Emissions during EoL

For PRE there is no overall factor (0.001) applied like for FPs, meaning PRE- emissions during landfill are 3.36% (33,600 ppm) which makes incineration the favored EoL situation even with RAC’s r -value for incineration (Table 6). We now sketch that the parameterized data model can address more complex questions as well. 500 t/a EoL emissions split to landfill (191 t/a), incineration (208 t/a), hazardous waste incineration (11 t/a), wastewater from the construction sector (70 t/a) and 19t/a

from the electronics sector where no more details are disclosed. This can be achieved by setting appropriate r-values for the other EoL-streams to zero.

If we now apply $r=100\text{ppm}$ for both types of incineration, emissions go down by 218 t/a. If further all landfilled waste is taken to incineration ($r=100\text{ppm}$), emissions go further down by 191 t/a.

As a EoL balance for PRE with all landfill waste being incinerated and incineration is at 100 ppm, 1.2 t/a remain from the originally incinerated fraction as emission and 0.6 t/a from the originally landfilled fraction, 70 t/a from wastewater from the construction sector and 19t/a from the electronics sector.

4.3. Scenario-based Distribution of PFAS Subgroups

Finally, the split between the emissions attributed to the different PFAS-subgroups, which was shown for the stage of the BD in 2.1. can be extended to the data provided by RAC and the two described scenarios (Table 7). For FP, the RAC-based reconstruction reduces FP-related PFAS emissions by 89.8% relative to the BD baseline, to 1,449 t/a. The “Conservative” and “Advanced” scenarios finally reduce FP-related emissions by 98.4% and 99.7%, corresponding to 228 t/a and 44 t/a, respectively.

Table 7: PFAS emissions in comparison to BD baseline as described in 2.1. RAC reconstruction is based on public European data and original RAC parameters. The granularity shown here is not published by RAC. Especially for FP a reduction of one order of magnitude can be unveiled. FP-based emissions can go further down by another order of magnitude if certain scenarios are considered. *The BD considers polymeric PFAS as a sum. With the parameterized data model and the f -factor set back to 1 the fraction of PFPE in the BD can be estimated.

PFAS Emissions	BD Baseline t/a	RAC Reconstruction t/a	Scenario “Conservative” t/a	Scenario “Advanced” t/a
PRE	7,153	7,180	6,995	6,962
GAS	46,195	58,603	58,603	58,602
FP	14,192*	1,449	228	44
PFPE	(937)*	937	895	888
Absolute sum	68,477	68,168	66,722	66,497

5. Critical Discussion

We could show that an emission-based life cycle assessment is possible for the PFAS subgroups PRE, GAS, FP and even PFPE. We could reproduce RAC data and validate our approach.

RAC’s opinion deserves particular attention. With unprecedented clarity RAC assigns FP, even microplastics FP, different behavior in the environment and different hazard profiles than other PFAS although all are persistent.

With the proposed parameterized data model, we provide decision makers with a cockpit where they can appreciate changing values for certain parameters and directly see consequences on emissions.

1 The scenarios discussed just show which type of information can be retrieved from the model. Even if
2 we use the same r-values for hazardous and non-hazardous incineration the parameterized data
3 model allows to treat the parameters separately.

4 There is no indication that other PFAS, other than PRE, GAS, FP, PFPE play a significant role in the
5 framework RAC is presenting.

6 The proportionality factors RAC is using can be discussed as well. This can only be a side aspect here.
7 The examples just show that our validation of the model is not meant to be a validation of RAC's raw
8 data itself since we do not have a comprehensive and independent database available. For all our
9 considerations in the model we go with the factors, RAC is assuming. The scenarios chosen certainly
10 show the effects of different settings.

- 11 – r-values. There are data sets where RAC criticizes the choice of r-values chosen by the BD authors
12 but refrains from adapting the data. This might have significant impact. Two examples are
13 presented: For FCM [10, p. 14] RAC disagrees with the chosen value of 0.136 and proposes 0.012
14 without correcting the value. Applying it to 2,895.5 t/a PRE results in an overestimation of 390 t/a
15 or 5% of PRE emissions. For medical devices RAC criticizes an excessive overestimation of
16 emissions to the environment [3, p. 53]. No correction is made for the selected ERC 5 release
17 factor (0.5). As a result, medical devices alone account for 3.8 of the 8.3 t/a for FP-related PROD
18 emissions across all use categories, as shown in detail in Table 1. ERC 5 means that 50% of the
19 used FP in PROD of medical devices end up uncontrolled in the environment which is considered
20 inconsistent or even unrealistic. It remains unclear why a 30- fold higher r-value for the
21 manufacture of medical devices is justified comparing it to PROD in transport or FCM. Interestingly
22 packaging for medical devices has a 500-fold lower r-value than medical devices themselves.
- 23 – f-factor. Setting it for FP to 0.001 is discussed by RAC [3, p. 53] extensively. It rejects smaller factors
24 like 1 ppm Henry et. al. found in finished FP-products [23]. RAC groups Henry with other literature
25 and argues that the detection limit for oligomers was not reported, which in parts is true for the
26 other literature, not for Henry's work in particular. RAC refers to OECD work on PVC [14]. PVC
27 needs plasticizers or flame retardants as additives which is far less required for FP. It is not unlikely
28 that the *f-factor* is significantly lower than assumed, which in particular would further reduce
29 emissions during PROD and U&S proportionate to the reduced factor.
- 30 – Percentage (p) value. According to the World Health Organization [24] about 15% of the waste
31 generated by health care activities as hazardous. RAC uses assumes 41.1% for products which
32 contribute most in EoL emissions of medical devices. For the purpose of our analysis this does not
33 have a relevant impact. It shows that assumptions can be challenged here as well.

34 For defining the baseline for emissions considering the BD we already make use of a later result
35 (Table 4) for the volume of PFPE (937 t/a). In contrast to FP, PFPE emissions are not sensitive (Table 7)
36 to the f-factor, so the back-projection ($f=1$) to achieve values for the baseline seems duly justified.

37 In our model RAW values for FP are overestimated but balanced by an equivalent underestimation of
38 PFPE RAW values. This is justified to not underestimate FP-emissions which is relevant to show that
39 overall FP-emissions get small. Finally, it is 6 t/a of FP-related RAW emissions in the scenario
40 "Conservative", any mistake made here could be considered minor.

41 RAC considers U&S emissions for FP as "very low"; its absolute value is determined to be 16t. This
42 value remains unchanged with the scenarios considered. Within that picture, PROD-emissions (8t)

should also be considered as very low. RAW emissions in scenario “Conservative” (6t) and EoL emission in scenario “Advanced” (18t) would also fall in this category. Both scenarios are within actual reach in Europe today. With that information a gap in the discussion if FP can be considered “polymers of low concern” can be diminished for a considerable part.

The scenarios chosen for FP might still overestimate emissions during EoL. Landfill emissions depend on the chosen *f-factor*, incineration is reported with even lower *r*-values down to 10^{-9} , as reported by Gemeinschaftskraftwerk Schweinfurt, a 32 year old legacy municipal waste incineration facility [18] in Bavaria.

For FP we therefore conclude that controlling emissions means controlling risk, especially for RAW and EoL. Meant as a result from our calculation model, not as a proposal for a restriction, a significant reduction (470 t/a) of PRE emissions is made if *r*-values for RAW are applied according to derogation (4m). Further reduction is possible considering the main contributors: TULAC consumer apparel (3,400 t/a), TULAC mixtures, their formulation and application (1,549 t/a). If for incineration $r=100\text{ppm}$ can be achieved and all PRE is incinerated (in favor of landfilling), a further reduction of 409 t/a is possible. This combined, would reduce all life cycle emissions for PRE by 5,828 t/a (-81%).

Emissions outside of the EU do not contribute but are relevant to products used within EU. In these metrics, used by RAC, it would be favorable to outsource RAW, PROD and EoL outside of EU. This can be shown in its sector specific opinion for transport [8, p. 19]. From 13,669 t/a of FP used in PROD 85% are manufactured outside of EU and are not considered for the reported emissions.

The six smallest use sectors are left out in our model contributing 185.6 t/a accounting for an error < 0.3%. With the eight additional sectors introduced by the BD authors which were not evaluated by RAC the situation will only slightly change because these new sectors contributing 5,289 t/a [3] (roughly 7%) are dominated by “other medical applications” (3,427 t/a) which itself are dominated by propellants for metered dose inhalers (3,420 t/a) according table A.80 in Ref [2]. So, GAS will dominate in the additional sectors as well, probably with a slightly lower percentage.

There is a 13% gap between the FP-baseline (14,109 t/a) versus the back projection of the parameterized data model with $f=1$ (15,966 t/a). Not having access to the data the BD authors use, and therefore not seeing which adaptations were made by RAC explains the gap. This has no influence in terms of understanding RAC’s final data and reconstructing our data model.

5. Conclusion and Outlook

RAC’s data provided in the sector specific opinions are of huge value to better understand details of PFAS-emissions. Other than RAC this approach, based on the same data set, considers emissions separately by PFAS subgroup and life cycle stage. This might be useful to readers and to those applying this data and the model.

We could not consider emission reductions based on PFAS-legislation that became effective after the restriction proposal was published in 2023. Such are e.g. EU 2024/573 (F-gases), EU 2024/2462 (PFHxA), EU 2025/40 (Packaging and Packaging Waste) which address relevant PFAS emissions already. Anyhow the legislator could implement their assumptions in the parameterized data model and run it for such type of adapted scenarios.

1

2 When emissions are regarded as proxy for risk, the findings about the drastically reduced emissions
3 from FP can no longer be regarded as unacceptable risk as REACH legislation requires [25]. We propose
4 that the situation needs to be reassessed with the new insights which strongly support the exclusion
5 of FP from the ECHA proposed PFAS restriction.

6

7 **Supporting Information**

8 Supporting Information for this article can be found under [...].

9 **Acknowledgements / Conflict of Interest**

10 The author is employed by the medical device manufacturer KARL STORZ SE & Co. KG, Germany and
11 chairman medical technology in the industry association SPECTARIS, Berlin.

12

1 **Symbols used**

2	E	emissions
3	f	f-factor
4	p	percentage for a certain pathway
5	r	release factor (RF)
6	V	volume

7 **Sub- and Superscripts**

8	I	use sector
9	j	sub-use
10	k	life cycle stage
11	l	PFAS subgroup
12	m	indicator for split pathways

13 **Abbreviations**

14	BD	PFAS Background Document
15	ECHA	European Chemicals Agency
16	EoL	end-of-life
17	ERC	environmental release categories
18	FCM	food contact material and packaging
19	FP	fluoropolymers
20	FPG	Fluoropolymer Product Group of Plastics Europe
21	f-factor	FP-factor introduced by RAC
22	GAS	Fluorinated gases
23	H	high value
24	L	low value
25	M	mid value
26	OECD	Organization for Economic Co-operation and Development
27	PFAS	per- and polyfluoroalkyl substances
28	PFPE	perfluoropolyethers

1	ppm	parts per million
2	PRE	Perfluoroalkyl acids and their precursors, including side-chain fluorinated polymers
3	PROD	product manufacturing
4	PVC	polyvinyl chloride
5	RAC	risk assessment committee
6	RAW	raw material production
7	RF	release factor
8	TULAC	textiles, upholstery, leather, apparel and carpets products
9	U&S	use & service life
10	VOL	volume

11

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1 Short text for the table of contents section

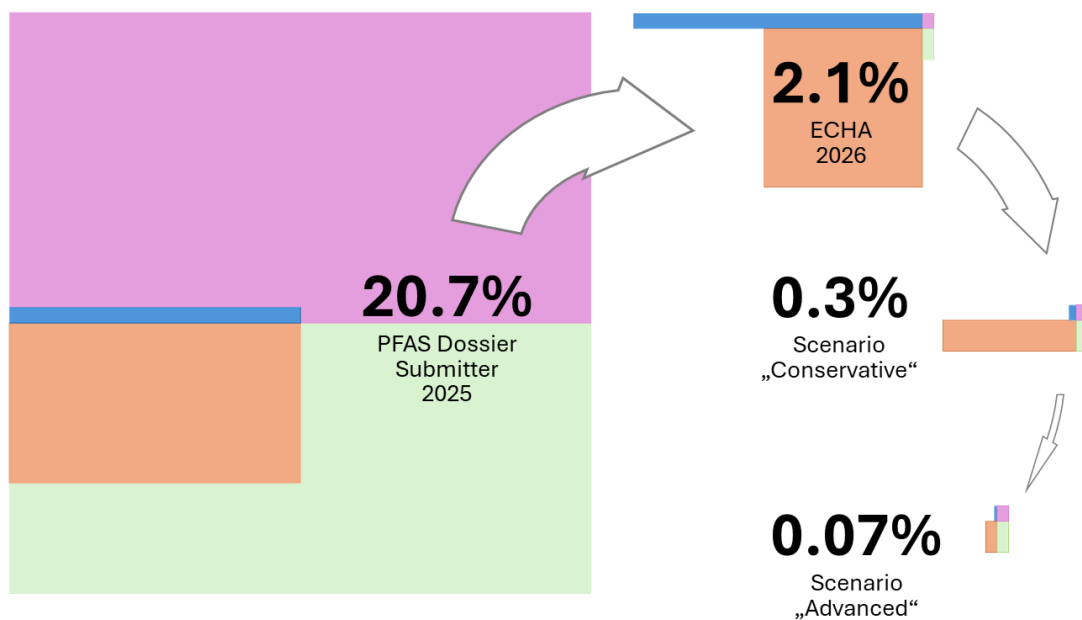
2 Parameterized Data Model for Enhanced PFAS-Emission Calculations Based on Public European
3 Data

4 Dr. rer. nat. Martin Leonhard^{1,*}

5 Extensive information on PFAS emissions is reconstructed. Compared to previous assumptions RAC's
6 alternative approach to fluoropolymers results in substantial reduction of fluoropolymer-based
7 emissions. Considering current technologies, emissions can further be reduced. Referring to the use
8 phase RAC describes them as "very small" already.

9

Fluoropolymer Emissions Overestimated



Life Cycle Emissions from Fluoropolymers:

Raw Material Manufacturing Product Manufacturing Use & Service End-of-Life

10