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Recovery of Fluorinated Refrigerants from Decommissioned RAC Equipment in Germany—Implications for National Emission Reporting under the UNFCCC

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Abstract: Germany is obliged to report emissions of fluorinated greenhouse gases annually under the UNFCCC. This includes emissions of fluorinated refrigerants when decommissioning RAC equipment. To obtain this information, data on the recovery, recycling, and disposal of fluorinated greenhouse gases is necessary, but such data are scarce. The VDKF-LEC database contains information on the recovery of fluorinated refrigerants from decommissioned RAC equipment in Germany and an extracted dataset was used to obtain real-world information for the years 2017 to 2021. Recovery rates for different fluorinated refrigerants from decommissioned commercial and industrial refrigeration as well as stationary air-conditioning equipment were derived. Furthermore, average lifetimes of equipment for the different sectors were calculated. In the analysis, a dependency of charged refrigerant and age of the unit at decommissioning could be observed. Results from the analysis of the VDKF-LEC dataset were compared with reported data under the UNFCCC for Germany and other available data sources.

Keywords: disposal; fluorinated greenhouse gases; F-gases; GHG emissions; GHG inventories; HFCs; RAC; recovery; refrigerants; refrigeration; air-conditioning

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1. Introduction

Fluorinated greenhouse gases (F-gases) are commonly used as refrigerants and foam-blowing agents. Among the group of F-gases, hydrofluorocarbons (HFCs) are the most widely used in refrigeration and air-conditioning (RAC) equipment, including heat pumps. HFCs were developed to replace ozone-depleting chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), and have large global warming potentials (GWPs), with trifluoromethane (HFC-23) having a GWP over a 100-year time horizon of 12,400 CO_2 equivalents [1]. Other commonly used HFCs and mixtures thereof have GWPs of around 700 to 4000 CO_2 equivalents. Based on worldwide projections considering current legislation, the contribution of HFCs (excluding HFC-23) to the global average surface warming amounts to 0.14 to 0.31 °C in the year 2100 [2].

Three main legislative frameworks are in place to reduce the use and emissions of F-gases in the European Union (EU) and Germany. Firstly, Regulation (EU) No 517/2014 (F-gas Regulation) [3] prohibits, among others, the use of F-gases exceeding certain GWPs in different applications from specified due dates and outlines an HFC phase-down process that limits the placing on the market of HFCs by distributing a quota based on CO_2 equivalents. This quota is periodically reduced according to a pre-defined schedule outlined in Annex V to the Regulation. To limit emissions during the lifetime of equipment and at disposal, the Regulation also requires operators of F-gas equipment to perform annual leak checks, keep detailed records, and ensure recovery of F-gases by certified personnel from, among others, stationary RAC equipment and refrigerated trucks and trailers. The F-gas Regulation is currently under review and extensions of bans and further tightening of the HFC phase-down schedule are expected [4]. Secondly, while the F-gas Regulation is directly enforceable in national law, the German Chemicals Climate Protection Ordinance (Chemikalien-Klimaschutzverordnung, ChemKlimaschutzV) [5] additionally outlines duties for F-gas equipment operators, e.g., emission threshold percentages and documentation requirements. Thirdly, the international Kigali Amendment to the Montreal Protocol to limit the consumption of ozone-depleting substances (ODS) introduced its own phase-down schedule for certain HFCs as replacement substances for ODS [6]. While the phase-down under the F-gas Regulation limits the placing on the market of HFCs, the Kigali phase-down limits the production and consumption of HFCs. Since these metrics are not identical (see respective definitions in [3,6]), Germany must ensure compliance with both phase-down schedules.

Ultimately, all policy measures are intended to reduce the emissions of F-gases to the atmosphere to curb global warming. Germany, as an Annex I party to the United Nations Framework Convention on Climate Change (UNFCCC), is obliged to report annual greenhouse gas emissions, including F-gases. Reporting takes place in so-called National Inventory Reports (NIRs) and follows the 2006 Guidelines set out by the Intergovernmental Panel on Climate Change (IPCC) [7]. NIRs are substantiated by data tables in a Common Reporting Format (CRF) that contain information on emissions by sources in metric tons and CO_2 equivalents for a 100-year time horizon [8]. From 31 December 2024, at the latest, reporting on GHG emissions will be conducted under the Enhanced Transparency Framework of the Paris Agreement [9], which will introduce Common Reporting Tables (CRTs) that replace the CRF tables, but no significant changes were made regarding F-gas emission reporting. Furthermore, from this date at the latest, all global warming potentials shall be calculated based on the Fifth IPCC Assessment Report [10].

To fulfill the reporting obligation under the UNFCCC, most countries, including Germany, employ a bottom-up stock model to quantify emissions of F-gases. In Germany, this model is commissioned by the German Environment Agency (UBA) and draws from different sources, such as the German Federal Statistical Office [11], publications by industry and science, different industry associations, and expert information. Top-down analyses of some commonly used HFCs have suggested that UNFCCC reported emissions for Annex I countries and Europe as a whole are largely consistent with atmospheric measurements [12,13], but discrepancies have been detected for individual European countries [14].

To improve the model and refine the underlying assumptions, real-world data are of the utmost importance. While emissions of F-gases from RAC equipment occur at first fill (manufacture), during operation, and at decommissioning, the present analysis focusses on the last step and aims to improve the model assumptions for end-of-life equipment.

One source of information on F-gases in the decommissioning process of RAC equipment is the operators of such equipment, who are obliged to recover fluorinated refrigerants, as set out in Art. 8(1) of the F-gas Regulation [3], for the purpose of recycling, reclamation, or disposal, and document the recovered quantities as well as the measures taken for recovery and disposal of these gases (as set out in Art. 6(1)). Recycling and reclamation differ in the extent of the treatment of the recovered gas. Following Art. 2 of the F-gas Regulation, recycling only involves a ”basic cleaning process”, while reclamation results in the gas regaining virgin status, i.e., being equivalent to novel gas.

The German RAC association “Verband Deutscher Kälte-Klima-Fachbetriebe e.V” (VDKF) hosts a database called VDKF-LEC [15], which contains information on RAC equipment that operators can voluntarily supply. Providing this data fulfills the record-keeping, reporting, and monitoring obligations set out by the F-gas Regulation and the ChemKlimaschutzV. Up until 28 March 2023, the VDKF-LEC database contained information on close to 239,000 units with a total charge of 2.5 kt of refrigerants [16].

To gather information on the disposal of RAC equipment and the associated fluorinated refrigerants, an extract of the VDKF-LEC database was analyzed with permission by the VDKF and compared with other available data. The results can enhance F-gas emission models and help to improve GHG emissions reporting for Germany under the UNFCCC and the Paris Agreement.

2. Materials and Methods

2.1. UNFCCC Reporting Based on the German F-Gas Model

Emissions in the German F-gas model are calculated by deriving sector- and equipment-specific stock data and emission factors. For emissions at disposal, the methodology follows the Tier 2a approach outlined in Chapter 7.5.2.1 of Volume 3 of the 2006 IPCC Guidelines [7]:

$$E_{\text{end of life},t} = M_{t-d} \cdot \frac{p}{100} \cdot \left(1 - \frac{\eta_{\text{rec},d}}{100}\right) \tag{1}$$

where $E_{\text{end of life},t}$ is the amount of refrigerant emitted at disposal in year t, M_{t-d} the amount of refrigerant initially charged into the unit installed in year $(t - d)$, d the lifetime of the unit, p the charge of refrigerant remaining in the unit at decommissioning, expressed in percentage of initial charge, and $\eta_{\text{rec},d}$ the ratio of recovered refrigerant relative to the quantity remaining in the unit at decommissioning.

The 2006 IPCC Guidelines [7] provide estimates on the variables in Equation (1) for RAC equipment in Table 7.9 of Volume 3. The estimates were updated for the mobile air-conditioning sector in the 2019 Refinement to the 2006 IPCC Guidelines [17] but remained the same for all other sectors.

2.2. VDKF-LEC Dataset

2.2.1. Description and Objectives

The dataset provided by the VDKF was an extract from the VDKF-LEC database containing information on the recovery of refrigerants from decommissioned RAC equipment. It contained unit-specific information on (1) type of refrigerant, (2) initial charge of refrigerant, i.e., the full charge size according to the type specifications of the unit, (3) quantity of refrigerant recovered from the disposed equipment, (4) destination of the recovered refrigerant, (5) sector, and partially subsector, in which the unit was used, and (6) estimated operating years of the unit, in most cases.

Analyzing the dataset followed two objectives:

1. Obtaining information on the recovered quantity of fluorinated greenhouse gases (F-gases or mixtures containing F-gases) from decommissioned refrigeration and air-conditioning equipment in Germany and the destination of the refrigerant, e.g., recycling, reclamation, and disposal.
2. Deriving averages for sector- and refrigerant-specific information on decommissioned refrigeration and air-conditioning equipment, i.e., average recovery rates for refrigerants and average operating years of decommissioned equipment.

Since no information on the refrigerant charge at the end of life of the unit was available, recovery rates could only be calculated with respect to the initial charge of the individual unit:

$$\text{Recovery rate } (\%) = \frac{\text{Refrigerant recovered at end of life (kg)}}{\text{Initial charge of refrigerant (kg)}} \cdot 100 \tag{2}$$

This contrasts with the recovery rate $\eta_{\text{rec},d}$ used in Formula (1), which relates to the quantity of refrigerant remaining in the unit at decommissioning.

2.2.2. Data Filtering

In a first step, units with refrigerants that were neither pure HFCs nor mixtures containing HFCs were removed from the dataset. Next, units for which the recovered refrigerant quantity exceeded the initial charge were removed. The dataset resulting from these first filtering steps was used for the analysis outlined in the first objective.

For the second objective, it was necessary to ensure that the averaged data were representative. For this purpose, the number of units recorded in the dataset for each refrigerant within the different sectors and subsectors was summed up over all years from 2017 to 2021. For any equipment type group (refrigerant within subsector within sector, for example, the refrigerant R410A in the subsector of decentral split units that are part of the sector "2.F.1.f Stationary air-conditioning"), with a sum below 25, the respective units were removed from the final dataset. This was to ensure that over the five-year span, on average, five units were represented per year. The rationale for this filtering strategy was that the dataset contained multiple instances where one year had less than five decommissioned units within an equipment type group but more than five in other years and a total of at least 25 units over all years. Removing these entries would have reduced the final dataset significantly.

This second filtering procedure was conducted for the recovery rates and the operating years of decommissioned units, respectively. Since information on operating years was not available for all units, this resulted in two different datasets. One for calculating average recovery rates and one for calculating average operating years.

The recovered amount of refrigerant in the VDKF-LEC dataset corresponds to the UNFCCC common reporting format (CRF) table category "Remaining in products at decommissioning" minus "Emissions from disposal" in Table 2(II)B-Hs2 for Germany [8]. The recovered quantities in the dataset are the amount of refrigerant that was extracted from the equipment at disposal and thus, emissions during the extraction process are not listed and already subtracted from the recovered amount. By comparing the VDKF-LEC and UNFCCC data, the representativeness of the VDKF-LEC dataset was assessed.

All data analysis was performed in R [18], using the packages *ggplot2* [19] for visualization and *multcomp* [20] for calculation of nonparametric bootstrapped 95% confidence intervals.

3. Results

3.1. Refrigerants

Regarding RAC equipment, different gases can be used as refrigerants in standard vapor-compression type units. Broadly, they can be differentiated between so-called "natural" and synthetic refrigerants. "Natural" refrigerants are naturally occurring substances, such as propane (C_3H_8), ammonia (NH_3), and carbon dioxide (CO_2). Synthetic refrigerants, on the other hand, are mostly hydrofluorocarbons (HFCs) and hydrofluoroolefins (HFOs) and mixtures thereof that do not occur naturally (Table 1) and were developed to replace chlorinated substances that deplete the ozone layer. HFCs are very potent greenhouse gases, while HFOs are less stable but often degrade to the highly persistent trifluoroacetic acid (TFA) [21]. For this analysis, only data on HFCs and mixtures containing HFCs and HFOs were used.

Table 1. Important fluorinated refrigerants and mixtures with their 100-year global warming potential (GWP_{100}) and common uses.

Refrigerant	Type	Constituents	GWP_{100} [1]	Common Use
R32	Pure gas	HFC-32 (CH_2F_2)	677	Stationary air-conditioning, part of mixtures
R125	Pure gas	HFC-125 (CF_3-CHF_2)	3170	Part of mixtures
R134a	Pure gas	HFC-134a (CF_3-CH_2F)	1300	Domestic (excl. standard fridges), commercial and industrial refrigeration, mobile air-conditioning (excl. passenger cars), sanitary hot water heat pumps, part of mixtures
R143a	Pure gas	HFC-143a (CF_3-CH_3)	4800	Part of mixtures
R1234yf	Pure gas	HFO-1234yf (CF_3CF=CH_2)	1	Mobile air-conditioning in passenger cars, part of mixtures

Table 1. *Cont.*

Refrigerant	Type	Constituents	GWP_{100} [1]	Common Use
R1234ze(E)	Pure gas	HFO-1234ze(E) ($CF_3CH{=}CF_2$)	1	Industrial refrigeration, stationary air-conditioning, part of mixtures
R404A	Mixture	44% HFC-125, 4% HFC-134a, 52% HFC143a	3943	Commercial and industrial refrigeration
R407C	Mixture	23% HFC-23, 25% HFC-125, 52% HFC-134a	1624	Stationary air-conditioning
R410A	Mixture	50% HFC-32, 50% HFC-125	1924	Stationary air-conditioning
R422D	Mixture	65% HFC-125, 32% HFC-134a, 3% R600a (C_4H_{10})	2473 [2]	Commercial and industrial refrigeration
R448A	Mixture	26% HFC-32, 26% HFC-125, 21% HFC-134a, 20% HFO-1234yf and 7% HFO-1234ze(E)	1273	Commercial and industrial refrigeration; retrofit for R507A and R404A
R449A	Mixture	24% HFC-32, 25% HFC-125, 26% HFC-134a, 25% HFO-1234yf	1282	Commercial and industrial refrigeration; retrofit for R507A and R404A
R454C	Mixture	21.5% HFC-32, 78.5% HFO-1234yf	146	Commercial refrigeration, stationary air-conditioning
R455A	Mixture	21.5% HFC-32, 75.5% HFO-1234yf, 3% CO_2	146	Commercial refrigeration, stationary air-conditioning
R507A [3]	Mixture	50% HFC-125, 50% HFC-143a	3985	Commercial refrigeration
R513A	Mixture	44% HFC-134a, 56% HFO-1234yf	573	Commercial and industrial refrigeration, stationary air-conditioning; retrofit for R134a

[1] Calculated according to the Fifth IPCC Assessment Report [1]; [2] Calculated using a GWP of 3 for R600a, as stated in Annex IV to the F-gas Regulation [3]; [3] Often labelled R507.

3.2. VDKF-LEC Dataset

Initially, the VDKF-LEC equipment dataset consisted of 6831 decommissioned units in different refrigeration and air-conditioning sectors. 746 units contained CFCs, HCFCs, natural, or unknown refrigerants and were removed from the dataset, as were 282 units with missing information on the type of equipment. After further quality checks and filtering, the dataset contained 5746 units for the years 2017 to 2021 in the UNFCCC sectors “2.F.1.a Commercial refrigeration”, “2.F.1.c Industrial refrigeration”, and “2.F.1.f Stationary air-conditioning” (Table 2, see Table S1 for a full list). Further filtering for the calculation of average recovery rates resulted in a total of 5365 units. Filtering for the calculation of average operating years, resulted in a total of 4611 units (Table S2).

Coverage over the years was largely consistent, with stationary air-conditioning being the most represented sector, mostly driven by decentral split units. The year 2018 showed the largest number of decommissioned units for all sectors but there is no clear trend visible over the years.

R404A was the dominant refrigerant in commercial refrigeration, followed by R134a. R449A is a comparatively newer mixture that was developed as a retrofit for R507A and R404A [22], and is available since 2014 [23]. As such, it was not frequently found in decommissioned equipment in the earlier years. Decommissioned industrial refrigeration equipment was mainly charged with R134a, followed by R407C and R404A. For stationary air-conditioning equipment, R407C and R410A were the most common refrigerants recovered at decommissioning, but some units also contained R134a. Other refrigerants were only sporadically listed for different equipment types (see Table S1).

Table 2. Number of decommissioned units filled with fluorinated refrigerants in the VDKF-LEC dataset for the different sectors and subsectors.

Equipment Type Group			Year					
Sector	**Subsector**	**Refrigerant**	**2017**	**2018**	**2019**	**2020**	**2021**	**Sum**
2.F.1.a Commercial refrigeration	Compound systems	R134a	27	39	43	26	43	178
		R404A	91	92	70	101	65	419
		R407C	20	15	11	3	18	67
		R422D	8	7	7	6	5	33
		R449A	0	3	4	12	7	26
		R507A	8	20	8	7	2	45
		Other	12	25	12	20	8	77
	Plug-in units	R134a	17	12	5	4	14	52
		R404A	9	21	22	12	19	83
		Other	13	4	8	5	5	35
2.F.1.c Industrial refrigeration	-	R134a	120	149	79	146	145	639
		R404A	22	19	16	30	19	106
		R407C	40	58	35	34	50	217
		R410A	4	9	7	8	6	34
		R422D	12	3	4	4	11	34
		Other	6	8	16	19	12	61
2.F.1.f Stationary air-conditioning	Decentral split units (single/multi)	R134a	35	44	30	45	25	179
		R407C	147	186	167	117	86	703
		R410A	290	396	388	361	357	1792
		Other	14	15	24	11	22	86
	Decentral VRF/VRV [1] units	R407C	9	9	8	8	6	40
		R410A	17	28	25	33	37	140
		Other	-	3	3	1	2	9
	Unspecified decentral units	R407C	14	8	6	4	4	36
		R410A	7	10	5	4	4	30
	Central air-handling units	R407C	17	18	19	20	14	88
		R410A	12	11	9	15	9	56
		Other	6	4	7	6	4	27
	Unspecified central units	R134a	7	17	14	55	35	128
		R407C	26	34	18	33	15	126
		R410A	27	13	16	18	13	87
		Other	3	6	4	5	3	21
	Unspecified units	Other	1	4	1	-	-	6
	Moveable units	Other	6	3	5	5	3	22
	Heat pumps (direct evaporation)	R410A	4	4	12	2	5	27
		Other	2	3	1	3	3	12
	Heat pumps (multi-circuit)	Other	3	8	1	7	6	25
Total			1056	1308	1110	1190	1082	5746
Total excluding "Other" refrigerants			990	1225	1028	1108	1014	5365

[1] VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively. "Other" refrigerants are at least two different refrigerants that each have a sum across all the years of less than 25.

Only very few heat pumps were listed as decommissioned in the dataset, which is reasonable since heat pumps have only been installed in larger numbers in Germany for a few years [24].

Looking at the sectors of refrigeration and air-conditioning, most of the recovered fluorinated refrigerants were disposed of (Figure 1, Table 3). Only a small share of the recovered gas from refrigeration equipment was recycled and even less reclaimed. For air-conditioning equipment, almost all the recovered gas was disposed of. Overall, the recovered amounts showed variation between years in the different sectors without any clear trend visible in the data.

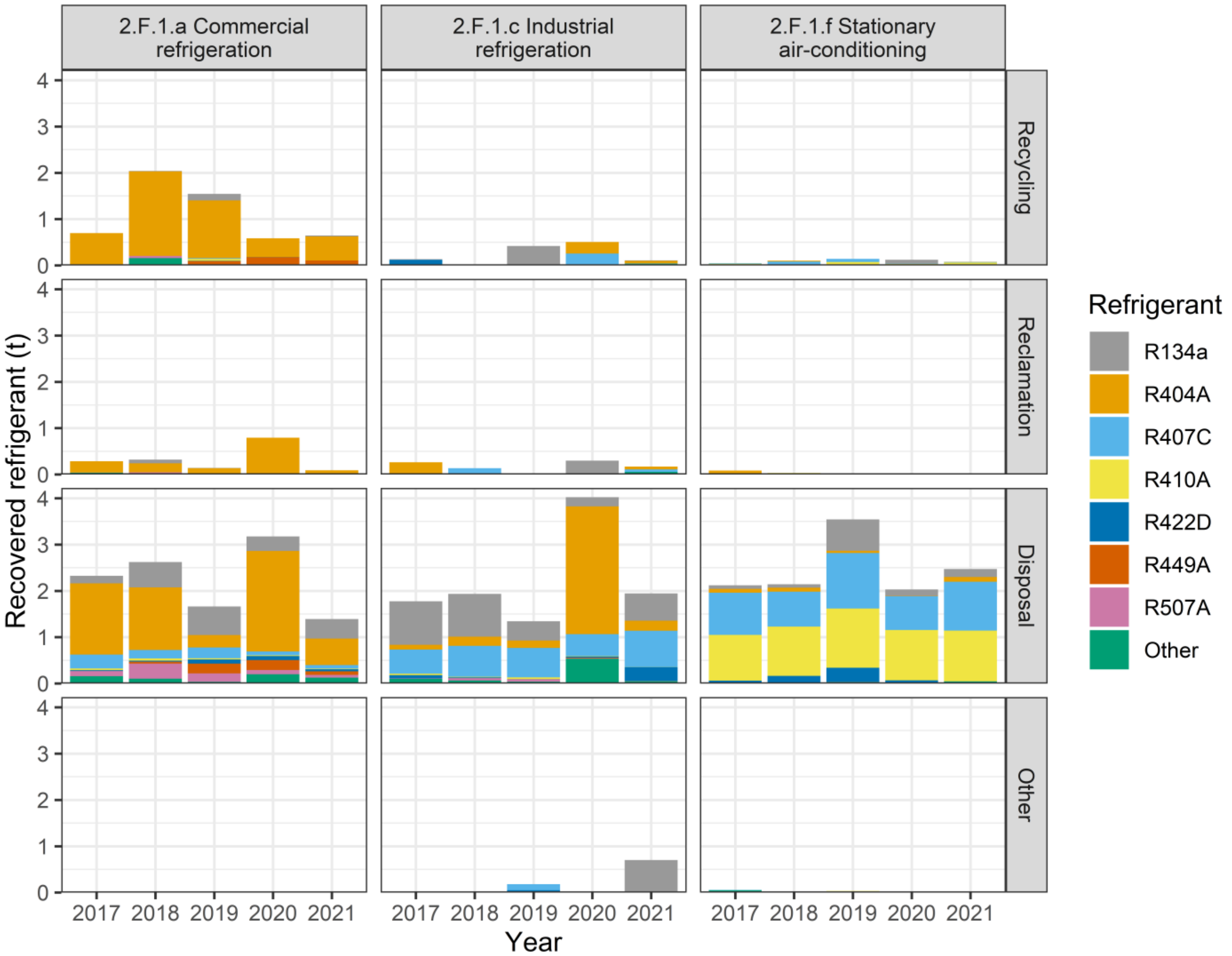

Figure 1. Recovered fluorinated refrigerants in different relevant sectors by destination and refrigerant in the VDKF-LEC dataset. For details on the destination "Other" see Table 3.

Noticeably, recycling and, to a lesser degree, reclamation of refrigerants mainly occurred for R404A in commercial refrigeration. Noteworthy are the years 2018, when R404A from commercial equipment was recycled in comparable quantities to disposal, and 2019, when R404A recycling far exceeded disposal. Disposal of recovered R404A from industrial refrigeration equipment showed a marked increase in the year 2020. However, this high value is mostly explained by the recovery of 1800 kg R404A from a single refrigeration unit, while four other units with recovered charges of 220 to 400 kg each also contributed significantly. Thus, the peak in recovery in 2020 was not due to an increase in decommissioned units, but rather the recovery of a few very large quantities from a handful of units.

The remaining destinations, labelled "Other" in Figure 1 and detailed in Table 3, cannot be further described since it is unknown where the recovered refrigerant ended up and whether it was recycled, reclaimed, or disposed of.

Table 3. Sums of recovered fluorinated refrigerants from decommissioned RAC equipment in the VDKF-LEC dataset in metric tons.

Sector	Destination	Year					
		2017	2018	2019	2020	2021	Sum
2.F.1.a Commercial refrigeration	Recycling	0.698	2.041	1.543	0.586	0.645	5.513
	Reclamation	0.287	0.320	0.142	0.795	0.090	1.633
	Disposal	2.324	2.624	1.663	3.176	1.392	11.178
	Other	-	0.018	-	0.001	-	0.019
	Retail	-	0.018	-	-	-	0.018
	Not specified	-	-	-	0.001	-	0.001
2.F.1.c Industrial refrigeration	Recycling	0.134	0.002	0.419	0.505	0.110	1.170
	Reclamation	0.262	0.136	-	0.299	0.170	0.867
	Disposal	1.775	1.934	1.344	4.021	1.944	11.017
	Other	-	0.001	0.180		0.700	0.881
	Producer	-	-	0.130	-	0.700	0.830
	Not specified	-	0.001	0.050	-	-	0.051
2.F.1.f Stationary air-conditioning	Recycling	0.047	0.104	0.141	0.123	0.076	0.491
	Reclamation	0.084	0.033	0.023	0.001	0.011	0.152
	Disposal	2.121	2.143	3.544	2.030	2.473	12.310
	Other	0.057	-	0.032	0.007	0.001	0.098
	Producer	0.050	-	0.032	-	-	0.083
	Not specified	0.007	-	-	0.007	0.001	0.015
Total	-	7.789	9.356	9.031	11.544	7.612	45.329

3.2.1. Recovery Rates of Refrigerants from Decommissioned Equipment

The quantity of recovered refrigerant relative to the initial charge from decommissioned equipment showed no clear trend over the years (Figure S1 and Table 4), and only few trends between refrigerant type in the VDKF-LEC dataset (Figure 2 and Table 4). With 88.1%, recovery rates for R449A from compound commercial refrigeration systems were, on average, higher than for other refrigerants. Compared to R507A and R404A, which R449A was designed to replace, the average recovery rate was 15.7% and 10.6% higher, respectively. R407C and R422D had the lowest recovery rate with 63.1% and 63.6%, respectively.

Table 4. Average share of recovered fluorinated refrigerants of the initial charge in decommissioned equipment in the VDKF-LEC dataset in percent.

Equipment Type Group			Year					
Sector	Subsector	Refrigerant	2017	2018	2019	2020	2021	Total
2.F.1.a Commercial refrigeration	Compound systems	R134a	86.5	70.7	73.7	77.0	64.3	73.2
		R404A	83.9	72.3	72.9	77.7	80.6	77.5
		R407C	84.0	66.8	72.5	83.3	27.8	63.1
		R422D	53.6	42.9	83.0	55.6	91.2	63.6
		R449A	-	90.8	92.2	91.0	79.5	88.1
		R507A	75.7	59.6	82.7	85.7	100	72.4
	Plug-in units	R134a	64.7	70.6	100	50.0	29.3	58.8
		R404A	77.8	56.2	80.0	87.1	84.3	75.7
2.F.1.c Industrial refrigeration	-	R134a	79.2	65.1	71.1	85.4	80.6	76.7
		R404A	81.3	75.0	84.4	80.5	60.5	76.7
		R407C	77.9	66.2	76.6	69.6	86.7	75.3
		R410A	57.2	58.1	78.1	49.3	41.7	57.2
		R422D	58.4	91.7	44.3	66.9	38.2	54.1
2.F.1.f Stationary air-conditioning	Decentral split units (single/multi)	R134a	100	97.7	100	89.4	96.0	96.2
		R407C	86.9	84.9	79.3	82.7	88.5	84.1
		R410A	82.8	82.4	85.3	81.9	82.3	83.0
	Decentral VRF/VRV [1] units	R407C	67.8	91.1	64.9	71.8	71.1	73.8
		R410A	74.1	72.6	80.5	75.7	85.1	78.2
	Unspecified decentral units	R407C	87.1	96.6	83.3	76.4	95.7	88.3
		R410A	98.7	82.4	75.7	75.0	100	86.4

Table 4. *Cont.*

Equipment Type Group			Year					
Sector	**Subsector**	**Refrigerant**	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**
2.F.1.f Stationary air-conditioning	Central air-handling units	R407C	66.7	70.6	69.2	83.4	86.8	75.0
		R410A	67.6	59.7	72.1	72.1	72.1	68.7
	Unspecified central units	R134a	57.1	94.1	50.3	49.6	53.1	56.9
		R407C	76.1	76.5	54.4	63.6	72.1	69.4
		R410A	81.5	53.8	75.0	66.7	75.1	72.1
	Heat pumps (direct evaporation)	R410A	75.0	75.0	91.7	52.7	60.0	78.0

[1] VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively. Information on the average initial charge of equipment can be found in the Supplementary Materials (Table S3).

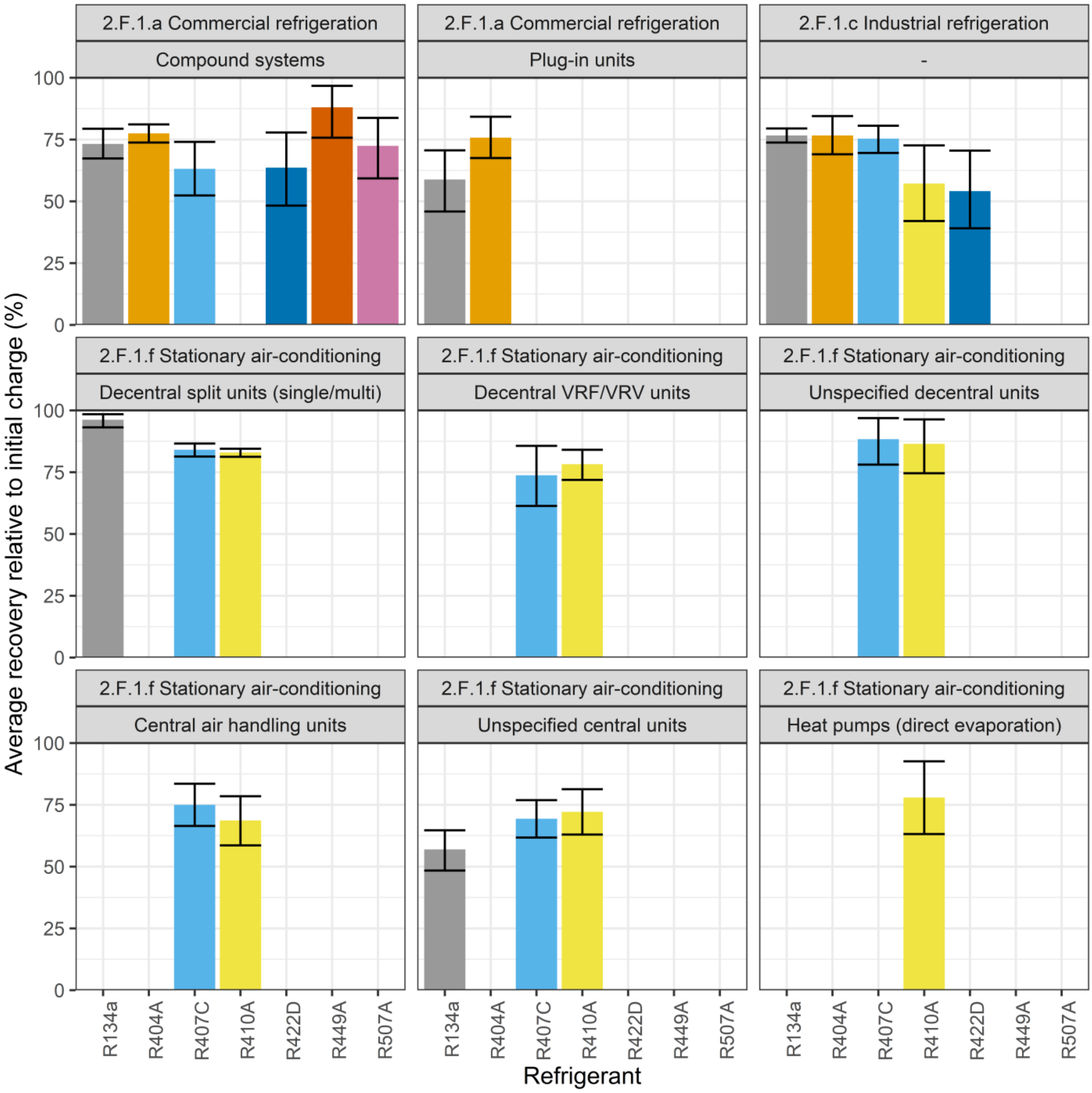

Figure 2. Average recovery of fluorinated refrigerant from decommissioned equipment relative to the initial charge over the years 2017 to 2021 for the different sectors and subsectors by type of refrigerant in the VDKF-LEC dataset. Error bars are nonparametric bootstrapped 95% confidence intervals for the group mean, based on 1000 bootstrap resamples. VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively.

For plug-in units, recovery rates for R134a were, on average, 16.9% lower than for R404A. For industrial refrigeration systems, R410A and R422D had, with an average 57.2% and 54.1%, respectively, lower recovery rates compared to other refrigerants that ranged between 75.3 and 76.7%.

For stationary air-conditioning, R410A and R407C were most frequently recovered from equipment, and the difference in recovery rate in the different subsectors showed no trend. It ranged between −6.3% for central air-handling units and 4.5% for decentral VRF7VRV (variable refrigerant flow/variable refrigerant volume) units. R134a was only recovered from decentral split units, where it had the highest recovery rates with an average of 96.2%, and unspecified central units, where it had the lowest, with an average of 56.9%.

Generally, it must be noted that in cases in which the initial charge exceeded the recovered quantities, it was unknown at which point of the life cycle the "missing" refrigerant emitted, since no further information on the recovery process was available. Most of the refrigerant remaining in equipment at decommissioning was very likely recovered, and thus, most of the emissions probably occurred during the lifetime of the equipment. However, emissions at disposal cannot be excluded, but no quantification was possible from the available data.

3.2.2. Operating Years of Decommissioned Equipment

It could be assumed that leakages leading to emissions of refrigerants during the lifetime of equipment increase in likelihood with operating years, mainly due to material fatigue. This would lead to lower refrigerant recovery rates for older equipment. This could be exacerbated by the possibility that servicing of equipment might not be a priority for very old units that will be decommissioned soon. Further assuming that all refrigerant is recovered at disposal, older units should, on average, have a lower ratio of recovery to initial charge (closer to zero on the y-axis in Figure 3). However, looking at the association between operating years and recovered refrigerants relative to the initial charge, this assumption cannot be substantiated by the data (Figure 3).

Only compound commercial refrigeration systems showed a trend of older units having less recovered refrigerant relative to the initial charge for units with a lifetime of under 30 years. The trend was reversed for older units but the coverage in terms of number of units was much less compared with younger equipment. Interestingly, plug-in units showed a trend of equipment with either a relatively short or long lifetime having a lower share of recovery, while industrial refrigeration equipment showed a slight trend of older equipment having a higher share of recovery but, as for compound systems, the coverage in terms of very old units was scarce.

Stationary air-conditioning equipment showed a trend of a higher share of recovery with operating years for some subsectors, such as central air-handling units and heat pumps. Other subsectors, such as decentral split and unspecified central units, showed this trend only for equipment with lifetimes below 10 years, or as was the case for decentral VRF/VRV units and unspecified decentral units, showed no trend at all.

Looking at the average operating years of decommissioned equipment, an association between type of refrigerant and lifetime of the unit could be observed (Figure 4 and Table 5). Compound commercial refrigeration systems with R407C had, on average, the longest lifetime with 17.3 years, but the difference was only 4.6 years between units with R407C compared to those with R507A, which had the shortest lifetime in this subsector. Notably, averaged over all years, R449A-units had a lifetime between that of R507A- and R404A-units. However, this can be misleading, since R449A was frequently used to retrofit existing R507A- and R404A-units. In such cases, the operating years in the VDKF-LEC dataset would refer to the entire lifetime of the unit, irrespective of the charged refrigerant. This is, for example, the case for the year 2018, where the average lifetime of R449A-units was 12 years (Table 5). Considering that R449A was only used from the year 2014, this average clearly includes retrofitted equipment and the time the unit was charged with R507A or R404A is included.

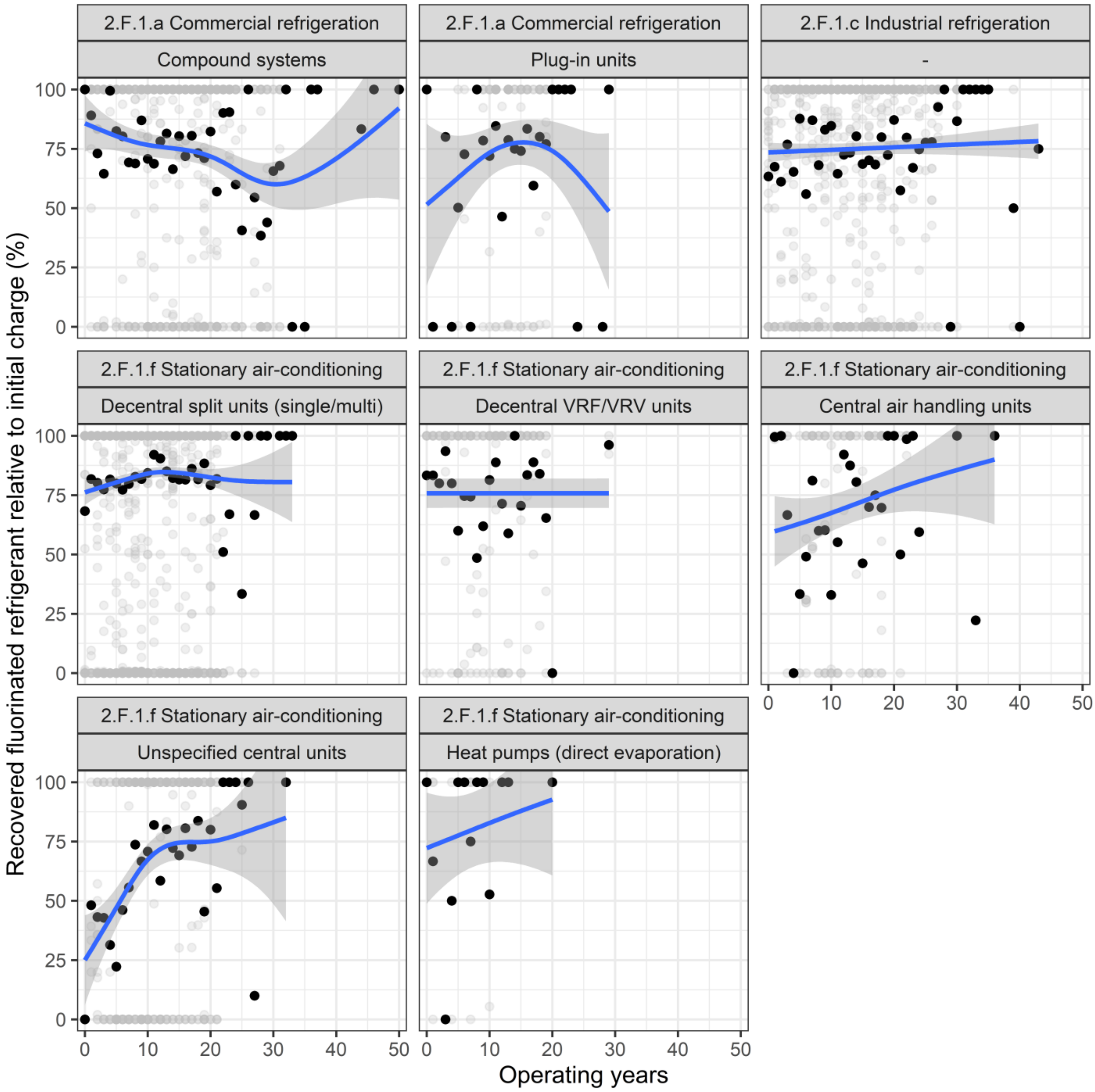

Figure 3. Association between operating years and recovered fluorinated refrigerant relative to initial charge for decommissioned equipment in the VDKF-LEC dataset. Grey dots are individual units, black dots are averages over units, and blue lines smoothed general additive model (GAM) fits with 95% confidence intervals. VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively.

Plug-in commercial refrigeration units with R404A had, on average, a 2.3 year longer lifetime compared to units with R134a.

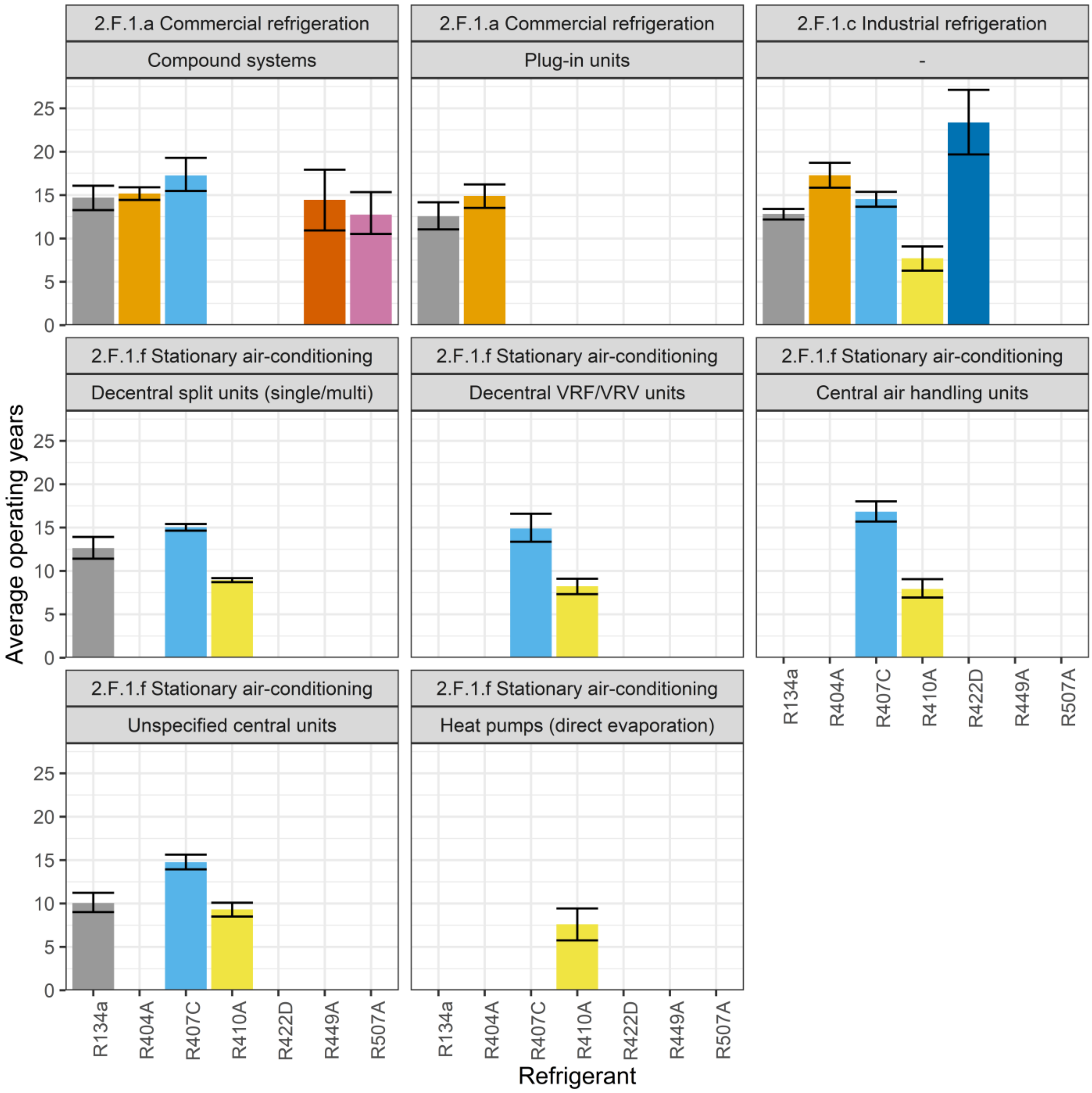

Figure 4. Average operating years of decommissioned equipment over the years 2017 to 2021 by sector, subsector, and refrigerant in the VDKF-LEC dataset. Error bars are nonparametric bootstrapped 95% confidence intervals for the group mean, based on 1000 bootstrap resamples. VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively.

In the sector of industrial refrigeration, R422D-units had, on average, the longest lifetime with 23.4 years. Units with other refrigerants had a shorter lifetime that ranged from 7.7 to 17.3 years. This trend could be observed for most, but not all years (Figure S2). Units with R410A had the shortest average lifetime with 7.7 years, but also the shortest lifetime within the individual years.

Table 5. Average operating years of decommissioned equipment in the VDKF-LEC dataset.

Equipment Type Group			Year					
Sector	**Subsector**	**Refrigerant**	**2017**	**2018**	**2019**	**2020**	**2021**	**Total**
2.F.1.a Commercial refrigeration	Compound systems	R134a	15.3	17.1	14.4	16.4	11.8	14.7
		R404A	12.2	15.8	13.5	17.1	16.8	15.2
		R407C	18.7	14.1	14.2	18.3	19.3	17.3
		R449A	-	12.0	18.2	12.1	17.0	14.4
		R507A	9.6	14.5	6.3	14.4	17.0	12.7
	Plug-in units	R134a	10.9	14.3	11.7	7.5	15.0	12.6
		R404A	11.7	18.4	12.0	16.1	15.3	14.9
2.F.1.c Industrial refrigeration	-	R134a	11.8	13.7	11.9	10.1	16.1	12.8
		R404A	15.7	15.3	14.1	18.6	21.9	17.3
		R407C	13.4	12.1	15.8	18.4	14.7	14.5
		R410A	7.5	8.2	8.0	6.2	8.6	7.7
		R422D	23.9	34.0	13.0	26.5	22.6	23.4
2.F.1.f Stationary air-conditioning	Decentral split units (single/multi)	R134a	9.0	10.1	15.2	13.4	12.7	12.6
		R407C	13.6	14.1	14.6	16.9	17.5	15.0
		R410A	8.1	7.9	9.1	9.3	10.1	8.9
	Decentral VRF/VRV [1] units	R407C	12.2	12.0	16.1	15.1	20.5	14.9
		R410A	8.4	6.8	6.5	9.5	9.5	8.2
	Central air-handling units	R407C	17.9	14.7	17.5	16.1	18.8	16.8
		R410A	8.6	6.1	11.3	5.9	9.0	7.9
	Unspecified central units	R134a	14.7	10.0	9.0	9.9	9.7	10.1
		R407C	15.5	13.0	16.6	15.4	14.3	14.8
		R410A	8.7	9.8	9.4	7.5	12.5	9.3
	Heat pumps (direct evaporation)	R410A	3.5	4.8	7.3	15.0	9.2	7.6

[1] VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively.

This trend could also be observed within the stationary air-conditioning subsectors. R410A-units consistently had a shorter lifetime compared to R407C-units, in all subsectors in which R407C-units existed (Figure 4 and Table 5), and this trend was consistent for all individual years (Figure S2). Looking at the mean operating years in Table 5, R410A-units lasted 5.5 to 8.9 years longer than R407C-units, for unspecified central units and central air-handling units, respectively. Stationary air-conditioning units with R134a were only present for decentral split units and unspecified central units and within these subsectors, their average lifetime was between units with R410A and R407C. For heat pumps, only units with R410A were present, so, no comparison was possible. The average lifetime of 7.6 years was, however, slightly lower than that for R410A-units in other subsectors of 8.9 years.

The reason for the shorter lifetime of R410A-equipment could be skewed sampling. For industrial refrigeration, this could be possible since R410A is strongly underrepresented in terms of recovered quantity. R410A makes up only 2.7% of the recovered R410A and R407C in this sector, and 0.8% of all recovered fluorinated refrigerants, using the filtered dataset for the calculation of averages. Thus, the shorter lifetime of R410A equipment could be due to biased sampling in this sector.

For the relevant stationary air-conditioning subsectors (Figure 5), recovered R410A is overrepresented in decentral split units (67% of the recovered refrigerant averaged over all years), VRF/VRV units (84%), and underrepresented in central air-handling units (14%) and unspecified central units (16%).

For central air-handling units and, to a lesser extent, for unspecific central units, the difference in operating years could be explained by the equipment type. In these subsectors, the R407C-units had a markedly higher average initial charge compared to R410A-units (Figure 6). This trend was not visible for the other subsectors, however.

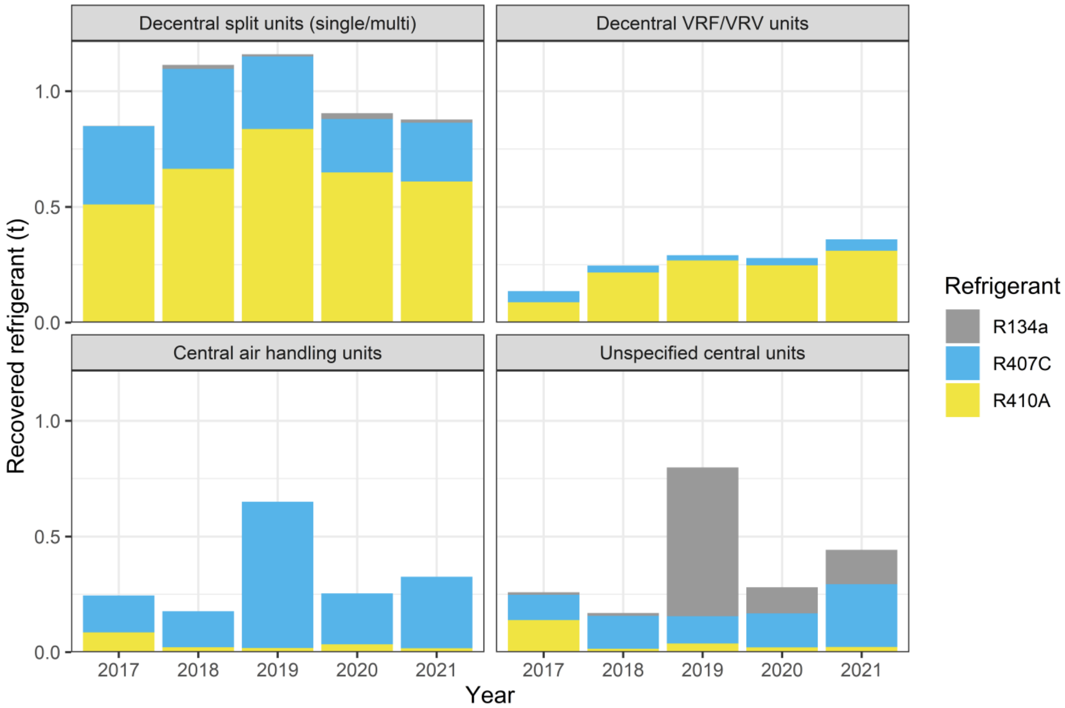

Figure 5. Recovered fluorinated refrigerants of stationary air-conditioning units based on the filtered VDKF-LEC dataset to calculate average operating years. Only subsectors with more than one refrigerant are shown. VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively.

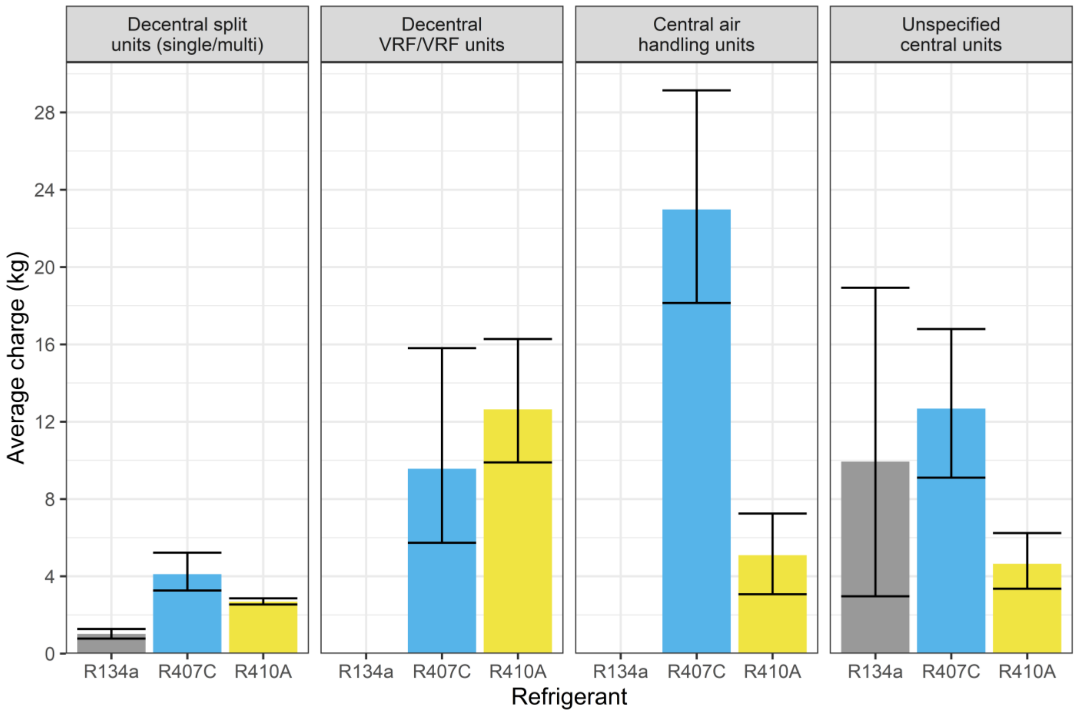

Figure 6. Average initial refrigerant charge of decommissioned stationary air-conditioning units in the VDKF-LEC dataset filtered for the calculation of average operating years. Only subsectors with more than one refrigerant are shown. Error bars are nonparametric bootstrapped 95% confidence intervals for the group mean, based on 1000 bootstrap resamples. VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively.

Another explanation could be the number of decommissioned units used for calculating average operating years. Looking at the number of units, there was indeed a large difference between refrigerant type within the split and VRF/VRV subsectors, in which the number of units with R410A strongly exceeded those with R407C (Figure 7). For the other subsectors, this difference was smaller but still present, although R410A units being represented less compared to the other refrigerants. However, representation of refrigerant type is quite good for all subsectors.

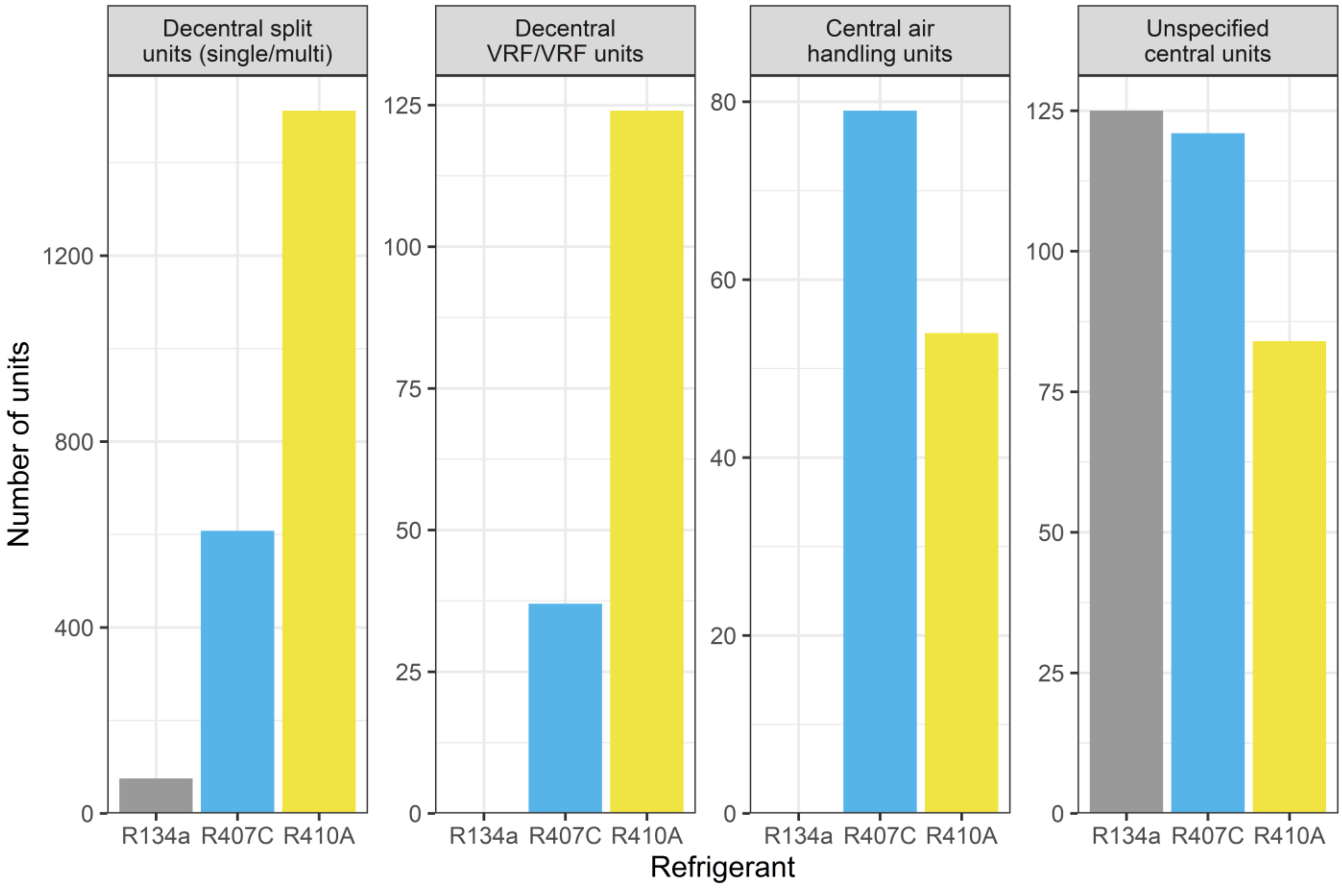

Figure 7. Number of decommissioned stationary air-conditioning units in the VDKF-LEC dataset filtered for the calculation of average operating years by type of refrigerant. Only subsectors with more than one refrigerant are shown. VRF and VRV stand for "variable refrigerant flow" and "variable refrigerant volume", respectively.

3.3. Comparison of the VDKF-LEC Dataset with Other Data Sources

Comparing the relevant sections of the UNFCCC CRF tables for Germany with the VDKF-LEC dataset, it becomes apparent that the dataset covers only around 0.7% of the fluorinated refrigerants reported as remaining in equipment at decommissioning (Table 6). For this comparison, mixtures were disaggregated by component (see Table 1) and only matching HFCs were used (HFC-23, HFC-32, HFC-125, HFC-134a, and HFC-143a). Coverage is best for the sector of industrial refrigeration, but generally, it appears that the VDKF-LEC dataset represents a relatively consistent, albeit small, share of the decommissioned equipment.

Table 6. Comparison of the HFC quantities reported in the UNFCCC common reporting format (CRF) table under the category "Remaining in products at decommissioning" minus "Emissions from disposal" in Table 2(II)B-Hs2 for Germany [8] and corresponding data for recovered HFCs from the VDKF-LEC dataset.

Sector	Source	Year					Average
		2017	2018	2019	2020	2021	
2.F.1.a Commercial refrigeration	UNFCCC total (t)	693.9	734.4	742.3	764.4	762.5	739.5
	VDKF-LEC (t)	3.2	4.9	3.2	4.4	2.1	3.56
	VDKF share of total (%)	0.5	0.7	0.4	0.6	0.3	0.5
2.F.1.c Industrial refrigeration	UNFCCC total (t)	86.3	175.9	176.0	175.2	181.7	159.0
	VDKF-LEC (t)	2.2	2.1	1.9	4.8	2.9	2.8
	VDKF share of total (%)	2.5	1.2	1.1	2.7	1.6	1.8
2.F.1.f Stationary air-conditioning	UNFCCC total (t)	386.0	386.5	404.2	511.7	565.3	450.7
	VDKF-LEC (t)	2.3	2.3	3.7	2.2	2.6	2.6
	VDKF share of total (%)	0.6	0.6	0.9	0.4	0.5	0.6
Total	UNFCCC total (t)	1166.2	1296.8	1322.4	1451.3	1509.5	1349.2
	VDKF-LEC total (t)	7.7	9.3	8.9	11.4	7.5	9.0
	VDKF share of total (%)	0.7	0.7	0.7	0.8	0.5	0.7

Note: Data on HFC quantities shown are only for matching HFCs in both datasets per sector (HFC-23, HFC-32, HFC-125, HFC-134a, and HFC-143a).

Looking at the entire VDKF-LEC database, it contained 146,409 units in May 2017 [16] and 175,622 in July 2018 [25]. For the year 2017, the German Mechanical Engineering Industry Association (VDMA) assumed that, excluding the sectors of domestic refrigeration and mobile air-conditioning, around 15.8 million RAC units were in use in Germany [26]. Comparing this number to the above-cited VDKF-LEC database numbers, it can be concluded that the VDKF-LEC database approximately represents a share of 0.9 to 1.1% of all RAC units for 2017 and 2018, respectively.

On a disaggregated HFC level, the VDKF-LEC dataset corresponds well in terms of included HFC composition (Figure 8). Differences occur in terms of fluctuation over the years, which is to be expected since the VDKF-LEC dataset contains real-life data, whereas the UNFCCC information is largely based on informed assumptions and extrapolations. As stated above, the unexpected high value of reclaimed HFCs in the industrial refrigeration sector in 2020 is mainly due to a few units with very large charge sizes, which translate into very large, recovered quantities. However, HFC-134a is generally reported relatively more for industrial refrigeration equipment in the VDKF-LEC dataset compared with the UNFCCC data. Conversely, HFC-134a is reported relatively less for stationary air-conditioning equipment.

Some HFCs were not included in one or the other dataset. HFC-227ea was listed in the UNFCCC dataset, albeit with minor quantities of 0.7 to 1.4 t for the years 2017 to 2021, but not in the VDKF-LEC dataset. HFC-152a, on the other hand, was included in the VDKF-LEC dataset in the sector commercial refrigeration with very small quantities of a few kg as part of the mixture R401A in the years 2018 and 2020, but not in the UNFCCC dataset. R401A is a mixture containing the ozone-depleting substances HCFC-22 ($CHClF_2$) and HCFC-124 (C_2HF_4Cl), which are prohibited for use in RAC equipment since 2015, as set out by Regulation (EC) No 1005/2009 [27]. Consequently, the units containing this mixture were installed between 1983 and 1997.

In order to compare the average recovery rates of HFCs relative to the initial charge as well as the average operating years of equipment from the VDKF-LEC dataset with the assumptions of the German and Czech F-gas models, averages for the assumed recovery rates and operating years were calculated for the German model and the Czech Phoenix model [28]. Just like the German model, the Czech model follows the 2006 IPCC Guidelines and uses the Tier 2a emission-factor approach to model emissions of F-gases [28]. More recent publications describing the model reported slight changes to the assumed emission factors for the different RAC sectors, while the assumed lifetimes of equipment did not change [29,30].

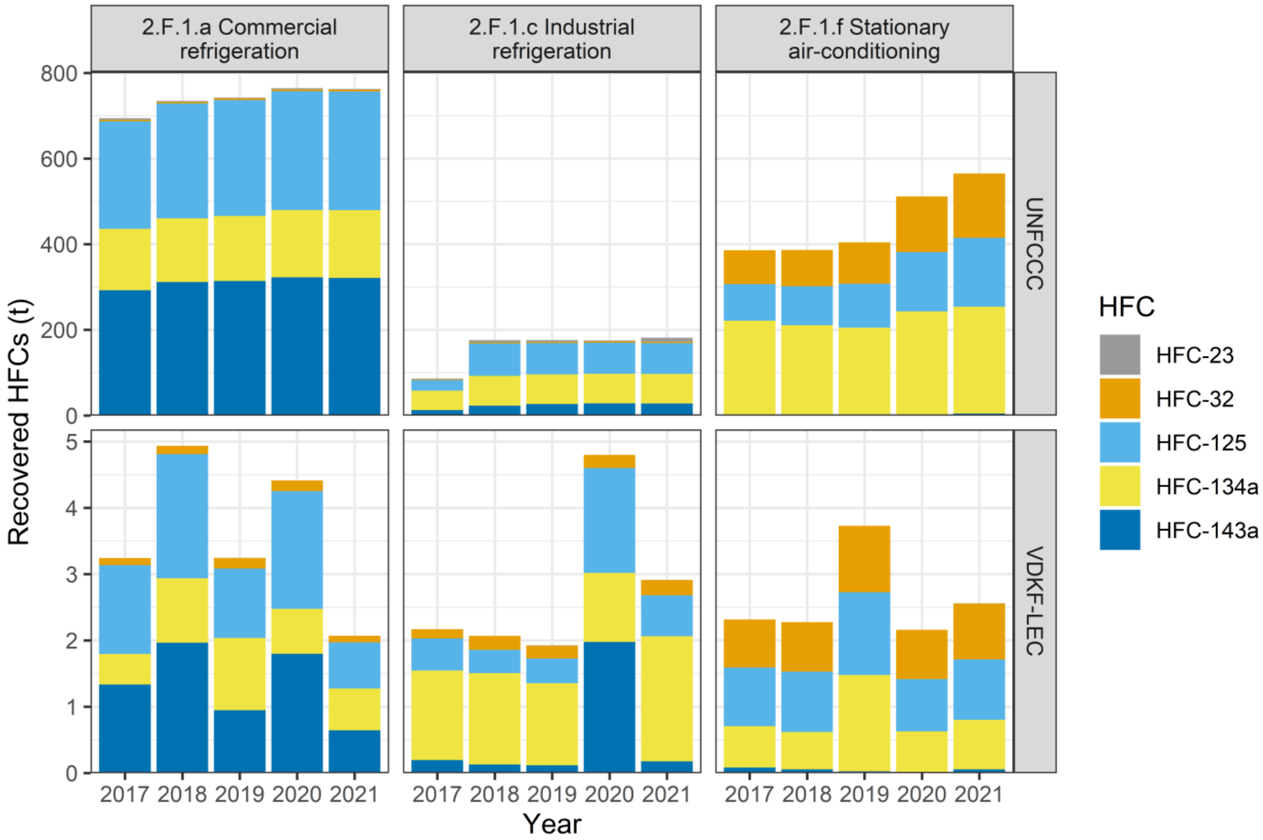

Figure 8. Comparison of the HFC quantities reported in the UNFCCC common reporting format (CRF) table under the category "Remaining in products at decommissioning" minus "Emissions from disposal" in Table 2(II)B-Hs2 for Germany [8] and corresponding data reported in the VDKF-LEC dataset disaggregated by individual HFCs.

Averaged over all subsectors, the VDKF-LEC dataset showed a 14% higher recovery rate compared to the German F-gas model for stationary air-conditioning while for commercial and industrial refrigeration, the recovery rate was 2.1% and 5% lower, respectively (Table 7). The Czech model recovery rates were identical for the different sectors and much lower compared to the VDKF-LEC data and the German model.

Regarding the operating years of equipment, the results were different depending on the sector. For commercial refrigeration, the VDKF-LEC dataset suggested a longer lifetime of equipment, compared to the German and Czech assumptions, with the Phoenix model having the shortest lifetime. For industrial refrigeration, the German model assumed the longest lifetime for equipment while the VDKF-LEC dataset suggested surprisingly short lifetimes for units in this sector. For the sector of stationary air-conditioning, the German and Czech model were well aligned but the lifetime calculated from the VDKF-LEC dataset was roughly 2.5 years shorter.

Interestingly, for operating years, commercial refrigeration equipment in the VDKF-LEC dataset was at the upper estimate of the 2006 IPCC Guidelines, but at the lower estimate for stationary air-conditioning equipment, and below the estimated range for industrial refrigeration equipment. Average recovery rates relative to the initial charge were much higher for commercial refrigeration and stationary air-conditioning equipment for both the VDKF-LEC dataset and the German F-gas model, but well within the assumed 2006 IPCC Guidelines rate for industrial refrigeration.

Table 7. Comparison of average recovery rates relative to the initial charge of F-gases ($\eta_{rec,d} \times p$) and average operating years of equipment (d) in the VDKF-LEC dataset (averages over the years 2017–2021), the German F-gas model (assumptions for 2020), the Czech Phoenix model (assumptions since 2018) [28,29], and the 2006 IPCC Guidelines [7] on a sector level.

Sector	VDKF-LEC Dataset		German F-Gas Model		Czech Phoenix Model		2006 IPCC Guidelines	
	$\eta_{rec,d} \times p$ (%)	d (Years)	$\eta_{rec,d} \times p$ (%)	d (Years)	$\eta_{rec,d} \times p$ (%)	d (Years)	$\eta_{rec,d} \times p$ (%)	d (Years)
2.F.1.a Commercial refrigeration	73.9	14.9 (7–23) [1]	76.0	12.0 (10–14) [2]	38.5	10.5	<63 [3]	7–15
2.F.1.c Industrial refrigeration	75.0	13.8 (6–22) [1]	80.0	15.0 (10–30) [2]	38.5	17.0	<92 [4]	15–30
2.F.1.f Stationary air-conditioning	81.5	10.9 (5–17) [1]	67.5	15.6 (10–25) [2]	38.5	13.5	<64 [5]	10–20

[1] Range from the average minus one standard deviation to the average plus one standard deviation. [2] Range over the different subsectors. [3] Average of $\eta_{rec,d} \times p$: 80% × 70% for stand-alone equipment and 70% × 100% for medium and large equipment. [4] Average of $\eta_{rec,d} \times p$: 90% × 100% for industrial refrigeration including food processing and cold storage equipment and 95% × 100% for chillers. [5] Average of $\eta_{rec,d} \times p$: 80% × 80% for residential and commercial air-conditioning including heat pumps.

Caution is warranted, however, since the averages for the German F-gas model in Table 7 were calculated over the respective subsectors without consideration of their relative importance. Calculating the sector averages using only the averages of the different subsectors for the VDKF-LEC dataset led to a 1.9% and 4.0% lower recovery rate for commercial refrigeration and stationary air-conditioning equipment, respectively. Regarding operating years, this approach led to a shorter lifetime of 0.3 years for both commercial refrigeration and stationary air-conditioning equipment. For industrial refrigeration equipment, no subsector information was available in the VDKF-LEC dataset.

For the Czech model rates, assumptions for recovery rates were based on expert opinion within the default ranges proposed in Table 7.9 of the 2006 IPCC Guidelines [28,30]. It was unclear whether the model assumed subsector-specific recovery rates and how the lifetime assumptions were derived. Thus, differences between the assumptions of the Czech model with the other sources in Table 7 could have been due to differing methodologies.

Looking closer at the industrial refrigeration sector, the VDKF-LEC dataset filtered for the calculation of lifetime averages, consisted mostly of R134a-units with 63.5% of the sector total, followed by R407C- and R404A-units (Table 8). Equipment with R410A and R422D was only represented with very few units that each accounted for less than 3% of the total and, upon exclusion, would result in an average lifetime of 13.7 years. Since most of the R134a-units were smaller systems, judging by their average charge size, with an average lifetime of 12.8 years, this explains the overall average lifetime of 13.8 years for industrial refrigeration equipment in the VDKF-LEC dataset.

Table 8. Details on the decommissioned units in the industrial refrigeration sector from the VDKF-LEC dataset filtered for the calculation of lifetime averages.

Refrigerant	Number of Units	Share of Total (%)	Average Lifetime (Years)	Range Lifetime (Years) [1]	Average Charge (kg)
R134a	629	63.5	12.8	5–21	9.7
R404A	103	10.4	17.3	10–25	48.4 (31.2) [2]
R407C	205	20.7	14.5	8–21	22.4
R410A	28	2.8	7.7	4–11	5.7
R422D	25	2.5	23.4	14–33	53.8
Total	990	100	13.8	6–22	17.4

[1] Range from the average minus one standard deviation to the average plus one standard deviation. [2] Excluding one unit with 1800 kg charge.

4. Discussion

Germany must report annually on emissions of F-gases under the UNFCCC. This includes the obligation to report on emissions at the decommissioning of RAC equipment. To obtain this information, data on the recovery, recycling, and disposal of F-gases are necessary but such data are scarce. The VDKF-LEC dataset contains information on recovery of F-gases and was used to obtain real-world data from decommissioned RAC equipment in Germany over the years 2017 to 2021.

4.1. Relevant Findings

Analysis of the dataset revealed that for the RAC sectors commercial and industrial refrigeration, and stationary air-conditioning, most of the recovered fluorinated refrigerants were disposed of, with some recycling mainly in commercial refrigeration equipment. Derived averages for recovery rates, relative to the initial charge of equipment showed no clear trend over the years or between type of equipment or refrigerant. Also, no clear association between amount of recovered refrigerant relative to the initial charge and operating years of the unit could be found.

However, a markedly shorter lifetime of equipment charged with R410A of five to nine years, compared to any other fluorinated refrigerant, could be observed across all years in most equipment types of the sectors industrial refrigeration and stationary air-conditioning. The reason for this effect is unknown and could be the result of a sampling bias. However, the fact that the effect is visible over multiple years in different subsectors and given that in decentral split units R410A is not heavily overrepresented, this suggests that there could be a real effect for stationary air-conditioning equipment. Analyzing more real-world data could shed light on this issue.

No clear association could be observed between the age of the equipment at decommissioning and the amount of recovered refrigerant, relative to the initial charge. Different sectors showed different trends, often even within the same sector, which made it impossible to draw relevant conclusions from this analysis.

The refrigerant R449A is a special case in that it was developed as a retrofit for the high-GWP refrigerants R507A and R404A in commercial and industrial refrigeration applications. While there are more replacement refrigerants that commonly include larger shares of HFOs to lower the GWP of the mixture, very few of them were present in the filtered VDKF-LEC dataset. For example, R448A was developed concurrently with R449A with the same purpose by a different manufacturer [31] but was only present in a total of five commercial and industrial refrigeration units in the VDKF-LEC dataset (see Table S1). Noticeable was the absence of R513A, which was available around the same time as R449A as a retrofit for R134a [32]. In the entire dataset, there was only one decommissioned central air-handling unit with R513A in the year 2019. Since the unit was installed in the year 2000, R513A was retrofitted. Lastly, R32 was found in only 22 decentral split air-conditioning units, one unspecified central air-conditioning unit, and one direct evaporation heat pump (Table S1). This finding was, however, expected since R32 is not a retrofit refrigerant but rather used in new equipment as a replacement for R410A. The earliest installation date for an R32-unit in the VDKF-LEC dataset was in July 2016 and it is expected that in future, increasingly more decommissioned R32-equipment will be reported on in the VDKF-LEC database. The same applies to R454C and R455A, as they were also designed for use in new equipment.

4.2. Representativeness and Comparison with Existing Data

Comparing the amount of recovered fluorinated refrigerants with the reported UNFCCC data, based on the German F-gas model, showed that the VDKF-LEC dataset covers less than 1% of the reported HFCs. As such, it is not representative of the total recovery operation in Germany for the analyzed sectors. However, it represents a relatively stable share of the operation over the years 2017 to 2021 and covers the relevant HFCs in the sectors, and as such, is valuable to draw conclusions from. However, the selection of reporters in the VDKF-LEC dataset could be overrepresented by more ambitious operators and recovery companies that opt for a sophisticated, digital system instead of common logbooks. Thus, it can be assumed that the recovery rates derived from the dataset are higher than the German average but, without further real-world data from other sources, no estimate on the extent of the deviation from the overall average is possible. This highlights the need for more analysis of data on decommissioned equipment.

Regarding the average recovery rate of refrigerants from commercial refrigeration units, the VDKF-LEC dataset aligned well with the German F-gas model, although the recovery rates were both exceeding the 2006 IPCC Guideline suggestion. Interestingly, the average recovery rate for industrial refrigeration units in the VDKF-LEC dataset was below the assumption in the German F-gas model, suggesting potential unaccounted emissions from this sector. Conversely, the VDKF-LEC dataset suggested higher recovery rates for decommissioned stationary air-conditioning units than those assumed in the German F-gas model. In terms of operating years of equipment, differences in the calculated average from the VDKF-LEC dataset and the German F-gas model assumptions could be observed.

4.3. Limitations and Outlook

As mentioned above, a comparison between the sector averages for recovery rate and lifetime from the VDKF-LEC dataset and the German F-gas model must be conducted with caution. For one, the selection of subsectors and refrigerants does not necessarily align. The VDKF-LEC dataset represents real-world data on recovered refrigerants from decommissioned equipment, whose type and charged refrigerant determines the resulting subsectors and refrigerants. This in turn is dependent on the availability and credence of such information. When either or both are lacking, the affected unit will not be accounted for in the statistics. In case of a systematic cause, such as poor recovery of specific types of equipment or extraction and recycling of refrigerant without reporting, certain subsectors or refrigerants could be unaccounted for in the VDKF-LEC dataset. The F-gas model, on the other hand, tries to capture all existing subsectors with their respective refrigerants and should provide a broader coverage compared to the VDKF-LEC dataset. This is substantiated by the fact that the VDKF-LEC dataset only represents a minor share of the total recovered amount of fluorinated refrigerants in Germany and that the VDKF-LEC database, in general, only represents around 1% of all RAC units in use.

Overall, the VDKF-LEC dataset only allowed the analysis of a subset of UNFCCC RAC sectors. Thus, there is a clear necessity to obtain more information on other sectors, such as domestic and transport refrigeration, and mobile air-conditioning. Furthermore, a more detailed representation of the industrial refrigeration sector would be valuable. As another suggestion for improvement, the refrigerant quantities remaining in the unit at the time of decommissioning should be added as a reported parameter. This would allow the calculation of recovery rates as outlined in the 2006 IPCC Guidelines [7].

Nonetheless, the results of this analysis will help in improving the underlying assumptions of the modelling of emissions of F-gases from decommissioned RAC equipment in Germany. This work should encourage more operators to opt for electronic reporting systems, such as the VDKF-LEC database, both within and outside Germany. As demonstrated here, electronic systems allow for a convenient and extensive analysis of large datasets that could not be achieved otherwise. Extending such databases, together with careful quality control measures and validation procedures, has the potential to greatly improve the bottom-up stock modelling of F-gas emissions.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/atmos15010035/s1, Table S1: Number of decommissioned units filled with fluorinated refrigerants in the VDKF-LEC dataset for the different sectors and subsectors; Table S2: Number of decommissioned units filled with fluorinated refrigerants in the VDKF-LEC dataset for the different sectors and subsectors. Shown is the dataset for the calculation of operating years; Table S3: Average initial charge of fluorinated refrigerants in decommissioned equipment in the VDKF-LEC dataset in kg; Figure S1: Average recovery of fluorinated refrigerant from decommissioned equipment relative to the initial charge for the different sectors and subsectors by type of refrigerant in the VDKF-LEC dataset. Error bars are nonparametric bootstrapped 95% confidence intervals for the group mean, based on 1000 bootstrap resamples; Figure S2: Average operating years of decommissioned equipment by sector, subsector, and refrigerant in the VDKF-LEC dataset. Error bars are nonparametric bootstrapped 95% confidence intervals for the group mean, based on 1000 bootstrap resamples.

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References

1. IPCC. *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
2. Velders, G.J.M.; Daniel, J.S.; Montzka, S.A.; Vimont, I.; Rigby, M.; Krummel, P.B.; Muhle, J.; O'Doherty, S.; Prinn, R.G.; Weiss, R.F.; et al. Projections of Hydrofluorocarbon (HFC) Emissions and the Resulting Global Warming Based on Recent Trends in Observed Abundances and Current Policies. *Atmos. Chem. Phys.* **2022**, *22*, 6087–6101. [CrossRef]
3. The European Parliament and the Council of the European Union. *Regulation (EU) No 517/2014 of the European Parliament and of the Council of 16 April 2014 on Fluorinated Greenhouse Gases and Repealing Regulation (EC) No 842/2006, Text with EEA Relevance*; Official Journal of the European Union: Strasbourg, France, 2014; Volume 150.
4. European Parliament. Review of EU Rules on Fluorinated Greenhouse Gases | Legislative Train Schedule. Available online: https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-review-of-eu-rules-on-fluorinated-greenhouse-gases (accessed on 18 December 2023).
5. Chemikalien-Klimaschutzverordnung vom 2. Juli 2008 (BGBl. I S. 1139), die zuletzt durch Artikel 299 der Verordnung vom 19. Juni 2020 (BGBl. I S. 1328) geändert worden ist. Available online: https://www.gesetze-im-internet.de/chemklimaschutzv/index.html (accessed on 21 November 2023).
6. Ozone Secretariat. Handbook for the Montreal Protocol on Substances That Deplete the Ozone Layer. In *The Secretariat for the Vienna Convention for the Protection of the Ozone Layer and for the Montreal Protocol on Substances that Deplete the Ozone Layer*, 14th ed.; United Nations Environment Programme: Nairobi, Kenya, 2020; p. 960.
7. IPCC. *2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme*; IGES: Hayama, Japan, 2006.
8. UNFCCC Germany. 2023 Common Reporting Format (CRF) Table | UNFCCC. Available online: https://unfccc.int/documents/627938 (accessed on 20 May 2023).
9. UNFCCC. *United Nations Reference Manual for the Enhanced Transparency Framework under the Paris Agreement—Understanding the Enhanced Transparency Framework and Its Linkages*; Version 2; United Nations Climate Change Secretariat: Bonn, Germany, 2022; Available online: https://unfccc.int/sites/default/files/resource/v2_ETFreferencemanual.pdf (accessed on 21 November 2023).
10. The Conference of the Parties. Decision 7/CP.27—Common Metrics Used to Calculate the Carbon Dioxide Equivalence of Anthropogenic Greenhouse Gas Emissions by Sources and Removals by Sinks. In Proceedings of the 9th Plenary Meeting, Sharm el Sheikh, Egypt, 17 November 2022; Available online: https://unfccc.int/sites/default/files/resource/cp2022_10a01_E.pdf?download (accessed on 19 December 2023).
11. Statistisches Bundesamt Substances Affecting the Climate. Available online: https://www.destatis.de/EN/Themes/Society-Environment/Environment/Substances-Affecting-Climate/_node.html (accessed on 21 November 2023).
12. Flerlage, H.; Velders, G.J.M.; de Boer, J. A Review of Bottom-up and Top-down Emission Estimates of Hydrofluorocarbons (HFCs) in Different Parts of the World. *Chemosphere* **2021**, *283*, 131208. [CrossRef] [PubMed]

13. Graziosi, F.; Arduini, J.; Furlani, F.; Giostra, U.; Cristofanelli, P.; Fang, X.; Hermanssen, O.; Lunder, C.; Maenhout, G.; O'Doherty, S.; et al. European Emissions of the Powerful Greenhouse Gases Hydrofluorocarbons Inferred from Atmospheric Measurements and Their Comparison with Annual National Reports to UNFCCC. *Atmos. Environ.* **2017**, *158*, 85–97. [CrossRef]
14. Brunner, D.; Arnold, T.; Henne, S.; Manning, A.; Thompson, R.L.; Maione, M.; O'Doherty, S.; Reimann, S. Comparison of Four Inverse Modelling Systems Applied to the Estimation of HFC-125, HFC-134a, and SF_6 Emissions over Europe. *Atmos. Chem. Phys.* **2017**, *17*, 10651–10674. [CrossRef]
15. VDKF e.V. VDKF-LEC. Available online: https://www.vdkf-lec.de/ (accessed on 21 November 2023).
16. VDKF e.V. Kältemittel-Emissionen aus Deutschen Kälte- und Klimaanlagen—Aktuelle Informationen über Leckageraten von 146.000 Kälteanlagen in Deutschland aus der im Mai 2017 vom VDKF Mittels der VDKF LEC Branchensoftware durchegführten Analyse. VDKF Information 2017, 7–8 Juli–August 2017.
17. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; IPCC: Geneva, Switzerland, 2019.
18. R Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2023.
19. Wickham, H. *Ggplot2: Elegant Graphics for Data Analysis*; Springer: New York, NY, USA, 2016.
20. Hothorn, T.; Bretz, F.; Westfall, P. Simultaneous Inference in General Parametric Models. *Biom. J.* **2008**, *50*, 346–363. [CrossRef] [PubMed]
21. Behringer, D.; Heydel, F.; Gschrey, B.; Osterheld, S.; Schwarz, W.; Warncke, K.; Freeling, F.; Nödler, K.; Henne, S.; Reimann, S.; et al. *Persistent Degradation Products of Halogenated Refrigerants and Blowing Agents in the Environment: Type, Environmental Concentrations, and Fate with Particular Regard to New Halogenated Substitutes with Low Global Warming Potential*; Texte | 36/2021; Umweltbundesamt: Dessau-Roßlau, Germany, 2021; p. 268.
22. Retrofit Refrigerant | Opteon^{TM} XP40 (R-449A). Available online: https://www.opteon.com/en/products/refrigerants/xp40 (accessed on 22 November 2023).
23. Everitt, N. DuPont's New Low GWP Refrigerant Trio. Available online: https://www.coolingpost.com/world-news/duponts-new-low-gwp-refrigerant-trio/ (accessed on 22 November 2023).
24. BWP. *Branchenstudie 2023: Marktentwicklung—Prognose—Handlungsempfehlungen*; Bundesverband Wärmepumpe (BWP) e. V.: Berlin, Germany, 2023.
25. VDKF, e.V. Analyse von Kältemittel-Emissionen der Kälte- und Klimaanlagen in Deutschland—Aktuelle Analyse von Nutzerdaten der VDKF LEC-Software von rund 39.000 Anlagenbetreibern mit mehr als 175.000 Kälte- und Klimaanlagen. VDKF Information 2018, 11–12 November–December 2018.
26. VDMA, e.V. *Energiebedarf Für Kältetechnik in Deutschland—Eine Abschätzung des Energiebedarfs von Kältetechnik in Deutschland nach Einsatzgebieten 2017*; Forschungsrat Kältetechnik e. V.: Frankfurt am Main, Deutschland, 2020.
27. The European Parliament and the Council of the European Union. *Regulation (EC) No 1005/2009 of the European Parliament and of the Council of 16 September 2009 on Substances That Deplete the Ozone Layer (Recast) (Text with EEA Relevance)*; Official Journal of the European Union: Luxembourg, 2017.
28. Ondrušová, B.; Krtková, E. The Phoenix Calculation Model for Emission Estimates of F-Gases Used in Refrigeration and Air Conditioning. *Meteorol. Zprávy* **2018**, *71*, 24–29.
29. Rošková, Z.; Schneider, J.; Štengel, M. Predicted Hydrofluorocarbon (HFC) and Perfluorocarbon (PFC) Emissions for the Years 2010–2050 in the Czech Republic. *Atmosphere* **2023**, *14*, 111. [CrossRef]
30. Müllerová, M.; Krtková, E.; Rošková, Z. F-Gases: Trends, Applications and Newly Applied Gases in the Czech Republic. *Atmosphere* **2020**, *11*, 455. [CrossRef]
31. Everitt, N. ASHRAE Proposes New R404A Replacements. Available online: https://www.coolingpost.com/world-news/ashrae-proposes-new-r404a-replacements/ (accessed on 22 November 2023).
32. Everitt, N. Emerson Lists R404A and R134a Alternatives. Available online: https://www.coolingpost.com/world-news/emerson-lists-r404a-and-r134a-alternatives/ (accessed on 22 November 2023).