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TFA contamination from fluorinated gases used in mobile air-conditioning systems **and already available PFAS-free alternatives**

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Summary

This white paper brings together two discussions that are usually handled separately: the proposed universal PFAS[1] restriction under European REACH regulation[2] and the choice of refrigerants in vehicle air-conditioning and heat pump systems. Hanon Systems' fleet assessment evaluates how different regulatory scenarios may influence future emissions of trifluoroacetic acid (TFA), a short-chain PFAS substance. The analysis recognizes that the legacy refrigerant R134a forms TFA only in part, whereas the newer R1234yf is converted almost completely to TFA in the atmosphere. TFA has been detected in European precipitation and archived environmental samples for decades, and current monitoring indicates a clear rise in concentrations.

But there are PFAS-free refrigerants available that do not cause TFA emissions. More than 1 million passenger cars with heat pump systems based on PFAS-free refrigerant R744 (CO_2), built with components from Hanon Systems and other Tier1 suppliers in VW, Audi, Škoda, Cupra and Ford vehicles are an excellent foundation for a PFAS-free future in the transport sector.

The following chapters explain the chemistry of TFA formation, outline the regulatory background, present the emission scenarios in detail, and discuss practical options for reducing PFAS-related risks in Europe's future vehicle fleet.

Key Findings

Regulatory urgency

Since implementing R1234yf in passenger vehicles in 2017, the annual TFA emissions are rising strongly. This will continue for the next ten years at least, unless a PFAS restriction leads to an early switch to natural refrigerants. Only a strict and timely adoption of natural refrigerants prior to 2035 could avoid an extremely high environmental TFA burden for the next decade.

Technical readiness

Thermal management systems[3] using the PFAS-free natural refrigerant R744 (CO_2) are already established in series applications in battery electric vehicles. Concepts using refrigerant R290 (propane) are under active development and validation. This shows that compliance with stricter PFAS regulation is technically achievable and more importantly, already available for the mass market.

Policy aspect

It is a fact that for all vehicles that use an electric compressor in their thermal management system, alternatives are available and have been proven over one million times in the field. This includes BEVs, PHEVs and all HEVs[4] with system voltages of at least 48 V. Comparison of regulatory scenarios indicates that refrigerant choice can reduce TFA emissions more quickly by making use of all these already available alternatives in all vehicles with an electric compressor.

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[1] PFAS: Per- and polyfluoroalkyl substances often called "forever chemicals"

[2] REACH: European Union Regulation (EC) No 1907/2006 on the Registration, Evaluation, Authorization and Restriction of Chemicals.

[3] Passenger vehicle thermal management systems use an integrated refrigerant circuit to cool the vehicle cabin, battery, power electronics and drivetrain. When equipped with heat pump functionality, the system can also provide energy-efficient heating.

[4] Battery electric vehicle (BEV), Plug-in hybrid electric vehicle (PHEV), hybrid electric vehicle (HEV)

1 Introduction

As one of only two global full-line automotive thermal solution suppliers, Hanon Systems aims to support the automotive industry with forward-looking thermal management solutions for a clean energy future. Guided by this vision, we have been working for more than 20 years on solutions based on alternative refrigerants that, in addition to a low GWP[5], are intended to avoid persistent fluorinated substances such as PFAS.

With this paper, we summarize our view of the refrigerants used in mobile applications, especially in passenger vehicles. Starting with a compact review of the history of refrigerants in this sector, we explain how the introduction of R1234yf leads to increased TFA formation and thus to a growing burden of TFA in the environment and, potentially, in the human body. This is followed by a presentation of a TFA emissions model for the passenger car fleet in Europe and its results. Different future scenarios are then used to quantify their effectiveness in reducing TFA emissions.

Finally, we present solutions that are already available and that enable a timely switch from PFAS-containing refrigerants to natural refrigerants.

Figure 1-1: A test vehicle containing a thermal management system utilizing PFAS-free refrigerant sits inside the Hanon Systems European Innovation Center's climatic wind tunnel

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[5] GWP: Global Warming Potential

2 History of mobile A/C system refrigerants

Since their introduction, air-conditioning systems in passenger cars have used fluorinated gases. Air-conditioning first entered the passenger car segment through luxury vehicles. In the beginning, existing technologies from other areas were simply transferred to vehicle applications. As A/C systems became more widespread, the relevance of the refrigerants used increased, and several environmentally critical developments were traced back to these refrigerants. Figure 2-1 shows the history of refrigerants used in mobile air-conditioning systems over the last 100 years and the related changes in legislation.

The first change was driven by the high ozone depletion potential of R12 (CFC[6]), which was used in mobile applications until 1987. The global phase-out of CFC refrigerants was adopted under the Montreal Protocol. [1]

R134a (HFC[7]) was introduced in mobile applications as the successor to R12. Only a few years later, the next environmental risk associated with refrigerants was identified.

R134a has a high global warming potential, and climate change became increasingly visible in public debate. The Kyoto Protocol, adopted in 1997, defined global greenhouse-gas reduction targets, and regional legislation was later introduced to phase out R134a. [2, 3] In this second change, R134a was replaced in new vehicles by R1234yf (HFO[8]). This reduced the global warming potential from 1 430 to 4.

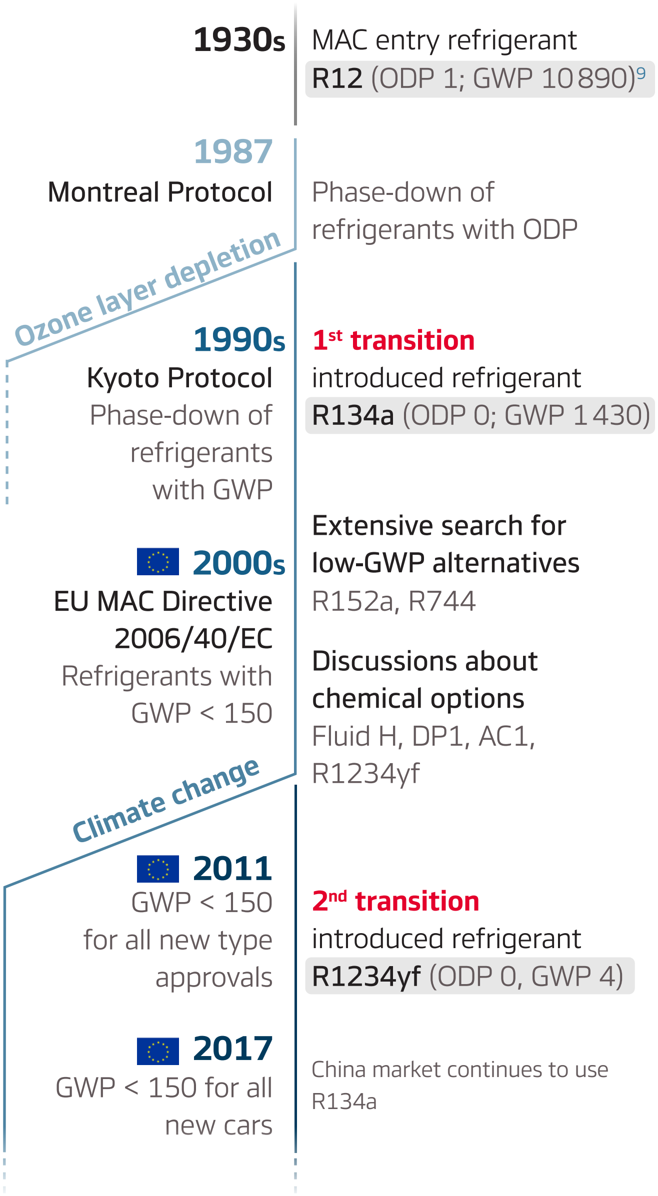

Figure 2-1: Historical transition of refrigerants in mobile air-conditioning systems and related regulatory drivers.

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[6] CFC: Chlorofluorocarbons are synthetic chemical compounds containing carbon, chlorine, and fluorine

[7] HFC: Hydrofluorocarbons are synthetic organic compounds that contain carbon, fluorine and hydrogen atoms, but no chlorine

[8] HFO: Hydrofluoroolefins are synthetic unsaturated organic compounds that contain carbon, fluorine, and hydrogen atoms and include at least one carbon-carbon double bond; they contain no chlorine

[9] ODP: Ozone Depletion Potential; GWP: Global Warming Potential

Only a few years later, PFAS, also known as “forever chemicals”, were identified as a health and environmental concern, and the use of fluorinated gases became one of the main contributors to PFAS emissions. In 2023, the EU began the process of developing a PFAS restriction targeting a broad ban on PFAS, subject to the availability of alternatives. This process is still ongoing.

The history of refrigerants used in mobile applications is a story of continuous change. Each new chemical refrigerant seemed to offer a solution at the time, but only a few years later it created a new reason for restriction or replacement. By contrast, natural refrigerants such as R744 (CO_2) and R290 (propane) are substances that exist in nature and therefore offer the potential for a long-term solution. With this third change, the goal is to establish a “forever refrigerant” and avoid the recurring cost of repeated transitions.

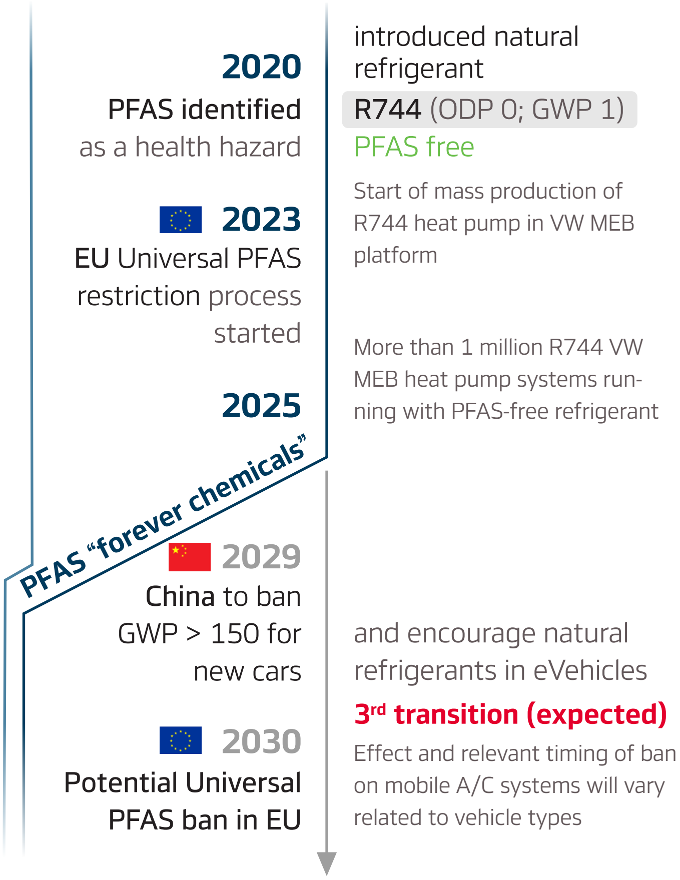

Figure 2-1 continued: Historical transition of refrigerants in mobile air-conditioning systems and related regulatory drivers.

3 What is the issue with R1234yf?

R1234yf is classified as a PFAS and would therefore be affected by a potential EU PFAS ban, like many other fluorinated substances. PFAS are persistent chemicals that lead to irreversible environmental exposure and accumulation. Due to their water solubility and mobility, contamination of surface water, groundwater, drinking water, and soil has occurred globally and is expected to continue. Once released into the environment, PFAS are very difficult and extremely costly to remove. PFAS have been documented as toxic and/or bioaccumulative substances with relevance to both human health and the environment. [4]

For the vehicle sector, where PFAS are used in various components, a potential PFAS ban will be particularly challenging. Unlike solid polymers or coatings, which largely remain with the vehicle, refrigerant systems are inherently slightly leaky during operation and even while parked. Depending on internal pressure conditions, vibrations during driving, and other factors, the system loses small amounts of refrigerant that are continuously released into the atmosphere over time. Vehicle users usually notice this process only after some time, when system performance declines and the refrigerant charge is refilled during servicing. This is a well-known phenomenon in passenger car refrigerant systems.

In addition to continuous leakage under normal operating conditions, crash events represent a further relevant emission pathway. One of the refrigerant heat exchangers is typically located in the front cooling module and may therefore be exposed to mechanical damage in frontal collisions. This typically results in the release of the full refrigerant charge. Although such events fall outside intended use, they occur in real-world traffic and should therefore be considered in the overall emission balance.

While these losses are almost imperceptible in a single vehicle, they become highly significant at a fleet level. Across millions of vehicles, this creates a continuous and relevant emission source.

Once released from the A/C system, the refrigerant enters the atmosphere, as indicated in Figure 3-1. Outside the closed system, it is present in the gas phase and disperses in ambient air. This atmospheric release enables subsequent degradation processes.

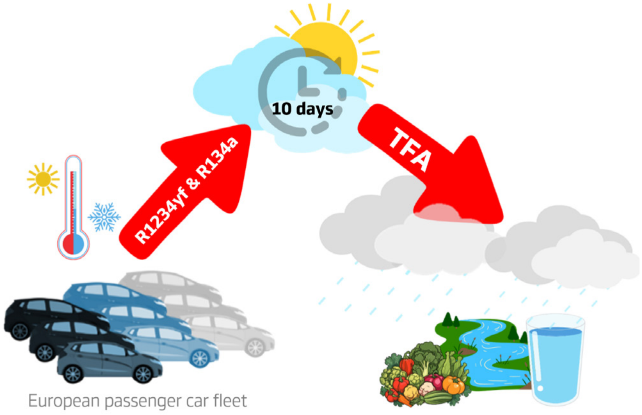

Figure 3-1: Schematic of the pathway linking vehicle refrigerant leakage to atmospheric TFA formation and subsequent deposition via precipitation.

3.1 Degradation mechanisms of R1234yf and R134a

What happens to the refrigerant once it has risen into the atmosphere? Figure 3-2 shows the atmospheric degradation processes of the refrigerants currently used. On the left, the degradation of R134a is shown. A key result is that only about 7-20% ends up as TFA [5], which is itself a PFAS. The remainder does not end up as a PFAS. The degradation of R1234yf is much more critical. This refrigerant is transformed almost completely into TFA, which means that it leads to more than five times as much TFA as R134a.

Furthermore, the degradation of R1234yf takes only about 10 days in the atmosphere and is therefore much faster than that of R134a, which takes about two to three months. Consequently, the TFA issue caused by refrigerants in vehicle air-conditioning systems escalated with the change from R134a to R1234yf, and shifted from a global to a more regional issue. Refrigerant emissions from European cars, for example, are deposited predominantly back in Europe.

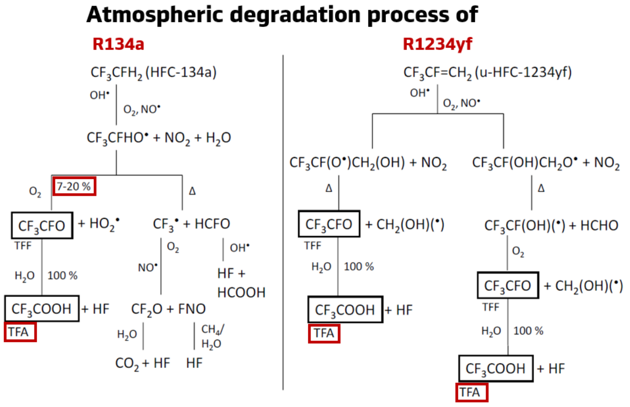

Figure 3-2: Atmospheric degradation pathways of R134a and R1234yf and the resulting TFA formation, based on Behringer et al. (2021) [5]

3.2 Wet deposition causes TFA concentrations in precipitation

As described above, the atmospheric degradation of fluorinated refrigerants results in the formation of TFA. A substantial fraction of this TFA is removed from the atmosphere by precipitation through wet deposition. This pathway is directly relevant for the occurrence of TFA in rainwater, which has been documented in both scientific studies and environmental monitoring. Fluorinated refrigerants used in passenger cars are by far the dominant source of TFA detected in precipitation, even if they are not the only contributor to the measured TFA load.

3.3 TFA modeling of the passenger car fleet in Europe

To better understand the impact of refrigerants in mobile air-conditioning systems in European vehicles on growing TFA concentrations in European precipitation and the associated accumulation of TFA in the environment, Hanon Systems developed a model to calculate and evaluate PFAS and TFA emissions from refrigerant leakages in passenger car cooling and heating systems. The main goal is to quantify current and future emissions and to show the impact of different future regulatory scenarios, as seen in Figure 3-3.

The model does not try to describe every technical detail of every vehicle and the individual impact. Instead, it provides a clear and practical picture of what happens at fleet level based on a small number of conservative assumptions.[10]

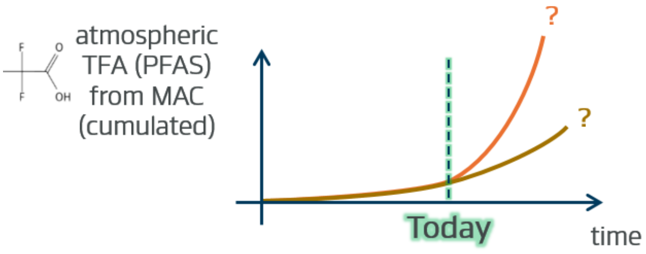

Figure 3-3: Qualitative representation of atmospheric TFA emissions from the European passenger car fleet for different scenarios.

The model focuses on passenger cars in Europe, including the EU27, the EFTA countries, and the United Kingdom. This market area was selected because TFA emissions from these passenger cars do not stop at the borders and affect TFA concentrations in European precipitation, the regional TFA effect described in Figure 3-1. In addition, current and historical vehicle registration data and fleet data are commonly available for this geographical scope, and technology trends are closely linked across these countries. At the same time, the regulatory background of the model is the current ECHA[11] universal PFAS restriction under discussion within REACH.

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[10] Model assumptions are introduced and explained in the Annex of this document (p. 31 ff.)

[11] ECHA: European Chemicals Agency

3.3.1 Projection of drivetrain distribution

The model derives its historical powertrain mix from publicly available data sets by ACEA[12] covering European passenger car registrations from the early 1990s to 2025 (see Annex, ASSUMPTION 5). [6] For the outlook beyond 2025, Hanon Systems extended this time series using internally developed forecasting assumptions, considering regulatory trajectories for the eventual ban of internal combustion engines in the EU [7], as shown in Figure 3-4.

In the reference scenario, this results in new registrations of ICE and conventional hybrids stopping in 2035. New plug-in hybrids are assumed to be registered for six additional years, until 2041. Market dynamics push battery-electric vehicles strongly. BEV shares rise from 22% in 2028 to around 70% in 2035, reaching 100% of new cars in 2041. The forward-looking, smoothed figures were tested in sensitivity analyses to help capture uncertainty.

3.3.2 Model results and evaluation approach

In line with the ECHA universal PFAS restriction proposal [8, 9], model results are evaluated over a period of 30 years, starting from a reasonable entry into force of the EU PFAS ban in 2028. This time horizon is necessary because factory-installed refrigerant systems are assumed to remain in vehicles for the entire vehicle lifetime, and refilling is assumed to be allowed under an unlimited derogation. Any new regulation is assumed to affect only new registrations, while older cars remain part of the fleet and continue to emit HFC and HFO refrigerant during their remaining lifetime.

The model therefore presents both annual emissions and cumulative PFAS emissions over time. This is especially relevant for persistent substances, because cumulative emissions help to show the long-term burden more clearly.

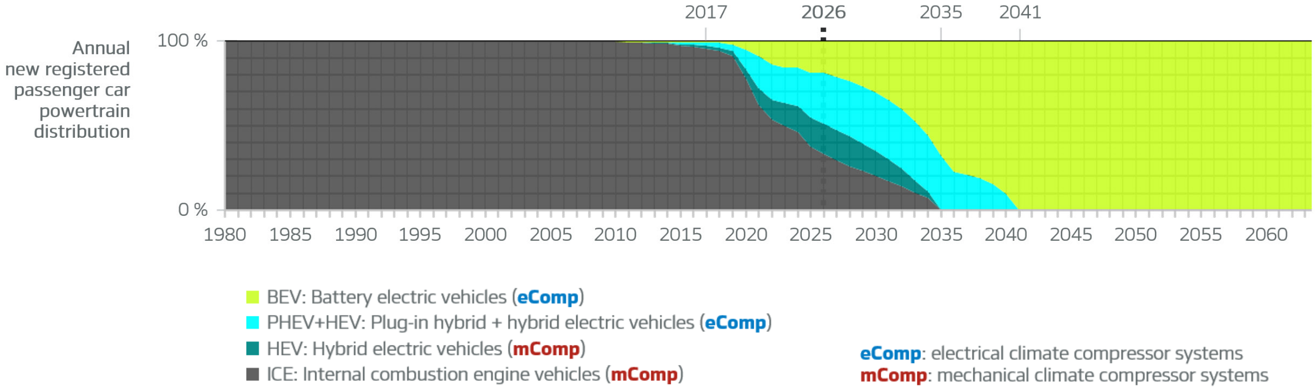

Figure 3-4: Historical and projected powertrain distribution of new passenger car registrations in Europe.

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[12] ACEA: European Automobile Manufacturers' Association

3.3.3 TFA emissions until today

Figure 3-5 shows the evolution of Europe's passenger car fleet, the regulatory switch from high-GWP R134a to low-GWP R1234yf, and the resulting TFA emissions. Until the mid-1990s, no TFA-relevant refrigerant was present. From 1993 onward, the introduction and increasing use of R134a-based A/C systems caused a slow but steady rise in annual TFA formation, visible in the pale-pink bars of the lower panel. As the air-conditioned vehicle fleet expanded through the 2000s, annual TFA releases climbed to roughly 2000 tons/a by 2010.

A noticeable change occurs after 2014, when new vehicle quotas for low-GWP refrigerants introduced under the EU MAC Directive trigger a steady transition to R1234yf. Because leaked R1234yf is converted almost completely into TFA in the atmosphere, TFA emissions rise sharply despite a relatively constant total mass of refrigerant lost from the fleet. By 2025, annual TFA emissions exceed 6000 tons/a, with R1234yf already accounting for more than 80% of the total emissions, but only 44% of the vehicle fleet.

Integrating the annual values yields a cumulative TFA load of approximately 68000 tons up to 2026. Of this, about half derive from historical R134a use, while the other half has accumulated during the brief but rapidly expanding era of R1234yf.

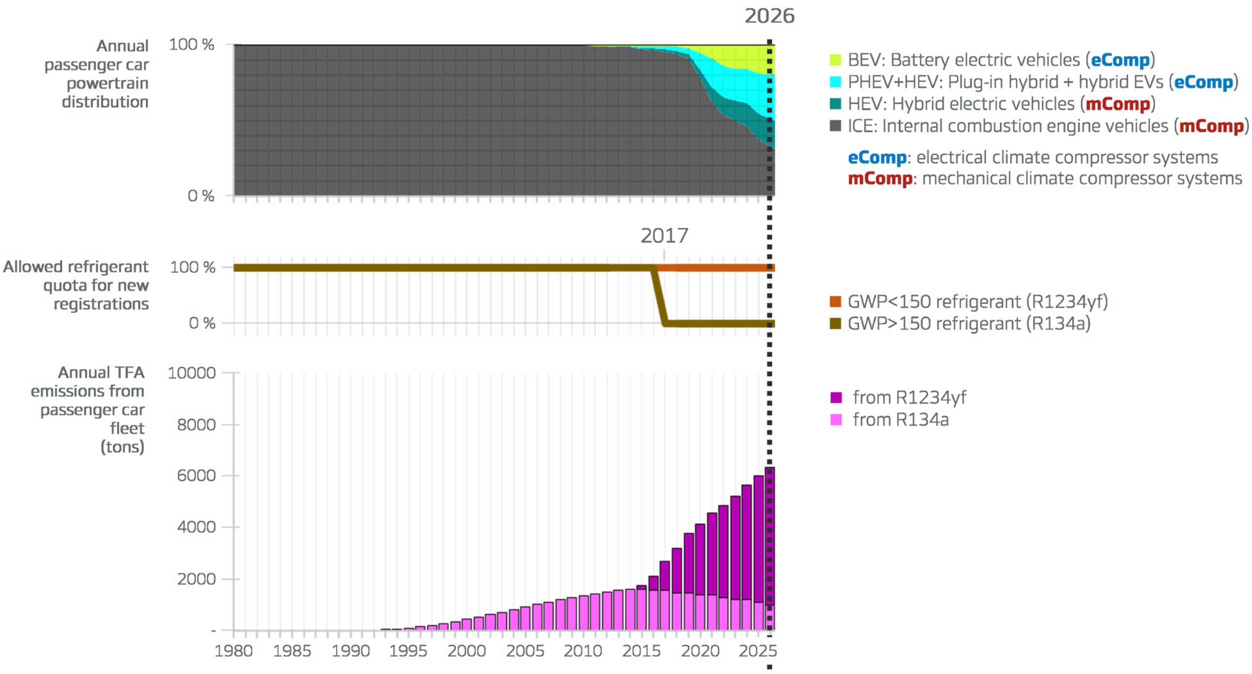

Figure 3-5: Historical powertrain mix of new registrations (top), allowed refrigerant quota (mid), and annual TFA emissions of the European passenger car fleet (bottom).

3.3.4 Projection of the next 30 years of TFA emissions – without PFAS regulation

The model compares three main scenarios. The first scenario is the baseline. In this case, there is no PFAS-related restriction for passenger car refrigerants. The historical shift from R134a to R1234yf continues to shape the fleet, but there is no additional regulatory push away from R1234yf.

Figure 3-6 shows the annual TFA emissions until the end of the 30-year evaluation period in 2058. Emissions rise until 2036 and exceed 9 000 tons/a. At that time, the full EU car fleet is transferred to R1234yf, except for a smaller number of cars built by the Volkswagen Group that continue to use R744. After the peak in 2036, TFA emissions decrease slightly because of fewer leakages due to increasing number of electric compressors replacing mechanical compressors and the corresponding lower leakage rate. Moreover, the overall car fleet volume is assumed to decrease (see Annex, ASSUMPTION 1).

Over the 30-year evaluation period, cumulative TFA emissions reach 240 000 tons. This would be 3.6 times more than the cumulative TFA load caused by the EU passenger car fleet over the previous 50 years.

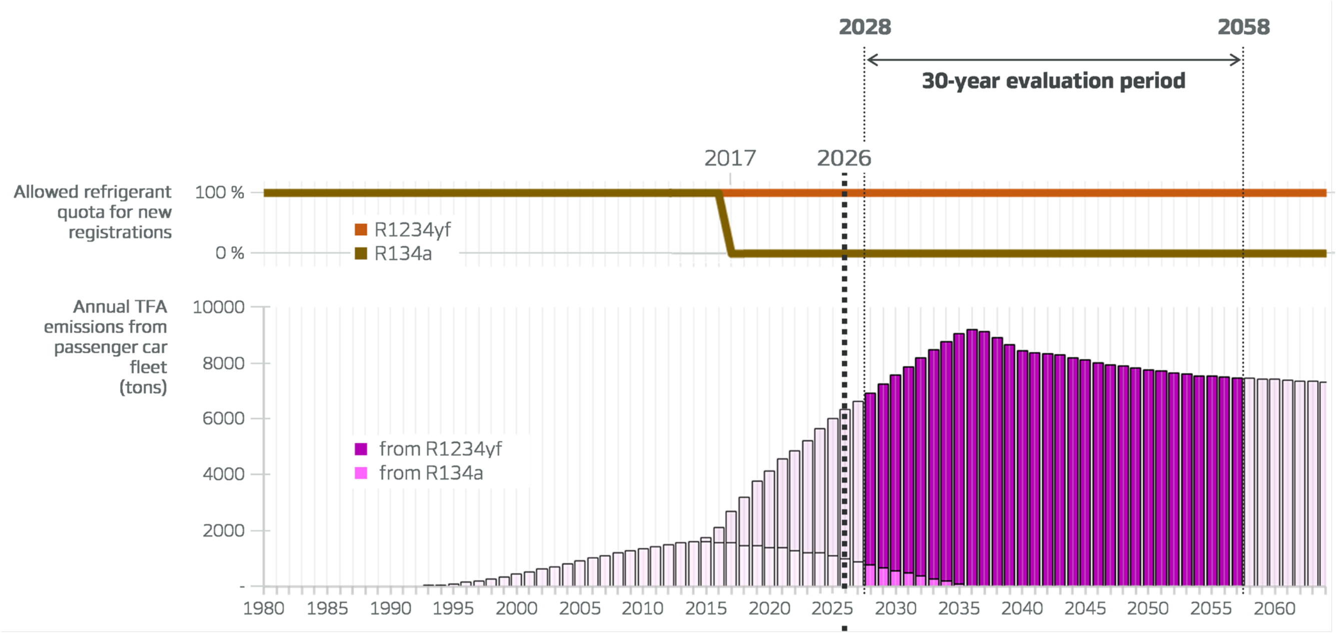

Figure 3-6: Projected annual TFA emissions from the European passenger car fleet without PFAS-related refrigerant restriction (baseline scenario).

3.3.5 Projection of the next 30 years of TFA emissions – based on RO1

The second scenario models Restriction Option 1 (RO1), as described in the ECHA PFAS restriction proposal documents. [8, 9] Under RO1, the model assumes a full ban after an 18-month transitional period[13]. Only the service of existing vehicles will continue with R1234yf after the ban date.

In the model, these regulatory approaches are translated into different phase-out timings for R1234yf in newly registered vehicles. Existing vehicles remain in the fleet until new vehicles gradually replace them. This is a strict but transparent way to show how different regulatory timelines can influence annual and cumulative emissions.

Modeling results are displayed in Figure 3-7. Here, annual TFA emissions under RO1 (purple bars) are compared with the baseline emissions (green bars). Consequently, the green area represents the avoided TFA emissions during the 30-year evaluation period.

Annual TFA emissions do not rise above 9 000 tons/a, because the restriction becomes active before the full vehicle fleet has transitioned to R1234yf. However, even this strict restriction option would still result in an accumulated TFA load of 102 000 tons during the evaluation period, which is 1.5 times more than the cumulative TFA load caused by the EU passenger car fleet over the previous 50 years.

Moreover, Figure 3-7 clearly shows the sharp increase in TFA emissions that followed the introduction of R1234yf into the European vehicle fleet. Even if a ban were to come into effect in 2030 according to RO1, approximately 15 years after the substance's introduction, the wave will only level off roughly two decades later. In total, this "TFA wave" caused by R1234yf spans at least 25 years, and only the first ten of those years have passed so far.

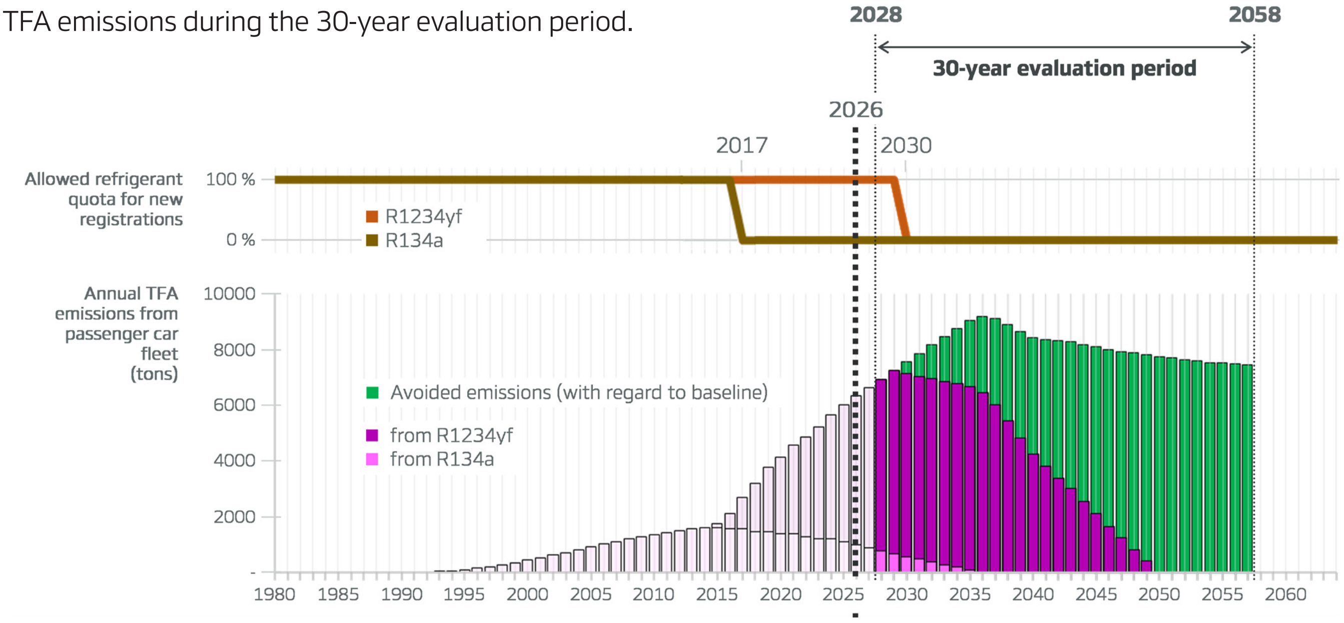

Figure 3-7: Projected annual TFA emissions from the European passenger car fleet under Restriction Option 1 (RO1). [9]

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[13] For simplicity, the 18 months are represented as 2 years after entry into force, meaning the full ban is active beginning with 2030.

3.3.6 Projection of the next 30 years of TFA emissions – based on RO2

The third scenario is Restriction Option 2 (RO2), which is also kept in line with the transport sector part of the ECHA documents. [9] In the 2023 Annex XV report, RO2 still differentiated mainly between refrigerant systems with electric compressors and those with mechanical compressors. In that older draft document, this meant no additional derogation for systems with electric compressors and a 5-year derogation for systems with mechanical compressors.

However, with the 2025 update of the draft Background Document (Version 14), this approach was changed into a derogation period of 5 years for BEV passenger cars, and a derogation period of 12 years applied to all other passenger cars. **Figure 3-8** shows the TFA emissions under RO2 (purple bars) based on this latest version of the ECHA document [9]. Again, the data are compared with the baseline, with the green area indicating the avoided TFA emissions.

Because of the derogations granted under RO2, annual TFA emissions continue to rise until 2036 although entry into force occurs in 2028. The TFA peak is nearly as high as in the baseline scenario without regulation.

Cumulative TFA emissions over the relevant 30-year period reach 143 000 tons, which is 2.1 times higher than during the previous 50 years. The PFAS restriction intention was registered around 2020, when a health concern had already been identified. The TFA emissions curve for RO2 shows that it would take until 2045, at least 25 years later, for annual TFA emissions from this sector to fall below the 2020 starting level. During the 25 years in between, the peak TFA emissions from this sector more than double.

It should be explicitly noted that the charts show annual fleet emissions, i.e., the rate at which cumulative emissions increase each year.

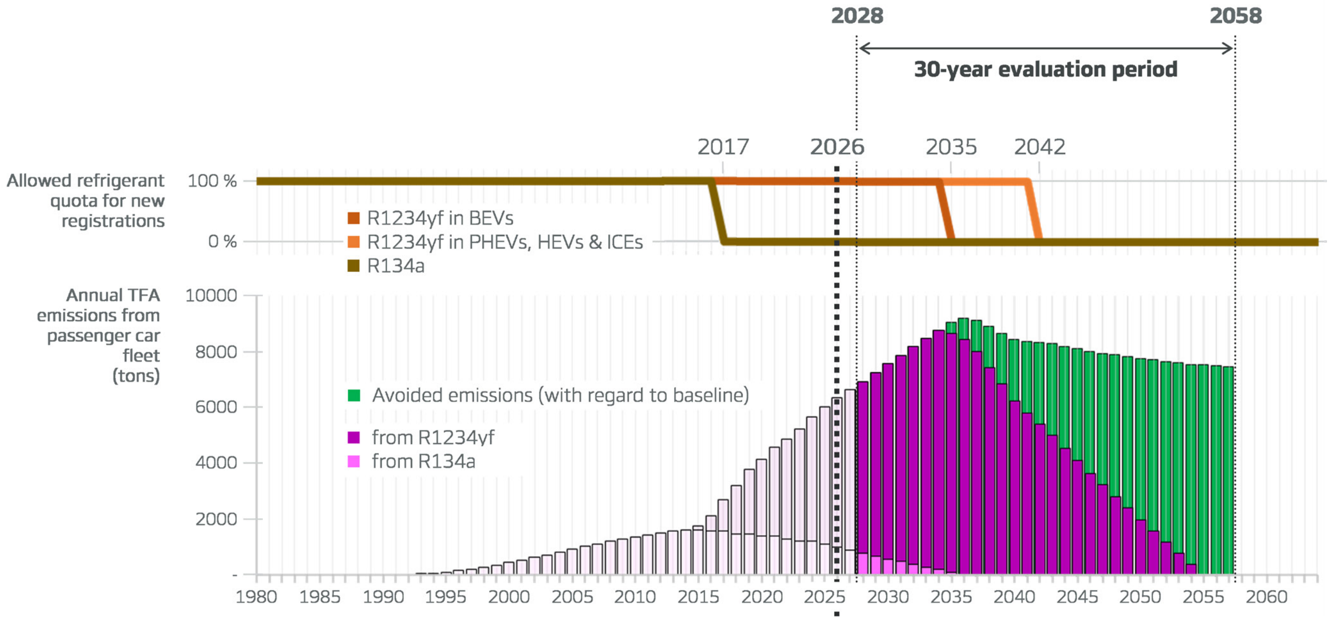


Figure 3-8: Projected annual TFA emissions from the European passenger car fleet under Restriction Option 2 (RO2). [9]

3.3.7 Model summary and limitations

Overall, the model provides a transparent way to estimate how passenger car refrigerant choices may influence future PFAS and TFA emissions in Europe. It combines public market data with explicit technical assumptions and a clear scenario logic. Most importantly, it shows that policy effects in this area depend not only on the refrigerant chosen for new vehicles, but also on fleet replacement and the long lifetime of vehicles already on the road. This fleet effect is central to understanding why the timing of regulation matters so much when cumulative emissions are considered.

A key finding is the need to convert as many vehicles as possible to alternative refrigerants before the entire fleet is converted to R1234yf by 2036. Only in this way can the enormous TFA emissions peak of more than 9000 tons/a truly be avoided.

The model also has defined limitations. It is not a full life-cycle model and does not include aspects such as production of refrigerants, leakages during vehicle manufacturing, detailed servicing procedures, end-of-life refrigerant recovery, or a detailed representation of atmospheric processes. It also does not model every manufacturer-specific system design. In addition, some inputs are simplified on purpose, such as the use of one representative charge value and generalized leakage rates. These are not hidden weaknesses. They are conscious simplifications made to keep the model understandable and useful for strategic scenario comparison.

Another uncertainty that should be considered when interpreting the results is that the rapidly increasing electrification of the EU vehicle fleet will cause a growing share of vehicles to be equipped with heat pumps. However, these systems often require considerably higher refrigerant charges. Vehicles with 1.2 kg or even more of R1234yf are already registered in Europe. This means that the expected annual TFA peak may in reality be significantly higher than 9000 tons/a. It should therefore be clearly stated that the present model carries a risk of underestimating future TFA emissions.

4 TFA measurements

Chapter 3.3 showed a continuous increase of TFA emissions caused by the European passenger car fleet in the last decade. The main reason is the switch to R1234yf, which is converted completely into TFA after release. Because of this, we expect a sharp increase in the amount of TFA that returns to the ground via wet deposition. The next question is whether this increase is already visible in the real world. Can higher TFA levels already be measured in precipitation, in natural materials such as soil and plants, or even in our food chain?

4.1 Precipitation

The distribution of annual precipitation in Europe is shown in Figure 4-1. It demonstrates that the Alpine region and the western coastal areas in particular receive the highest amounts of precipitation. Precipitation in the Alps is especially important because this is where major European rivers such as the Danube, the Rhône, and the Rhine have their sources. Bank filtrates from these major rivers are a key source for agriculture and drinking water.

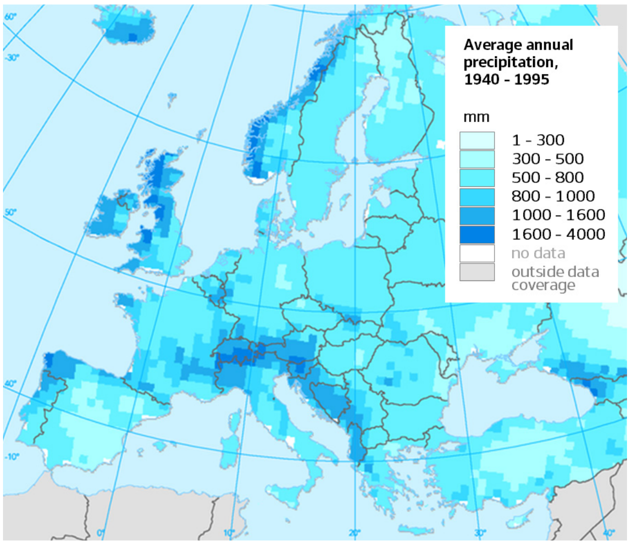


Figure 4-1: Average annual precipitation distribution in Europe, source: European Environment Agency [10]

Detailed measurement data on TFA concentrations in rainwater at selected locations in Switzerland reported by Henne et al. [11] are shown in Figure 4-2.

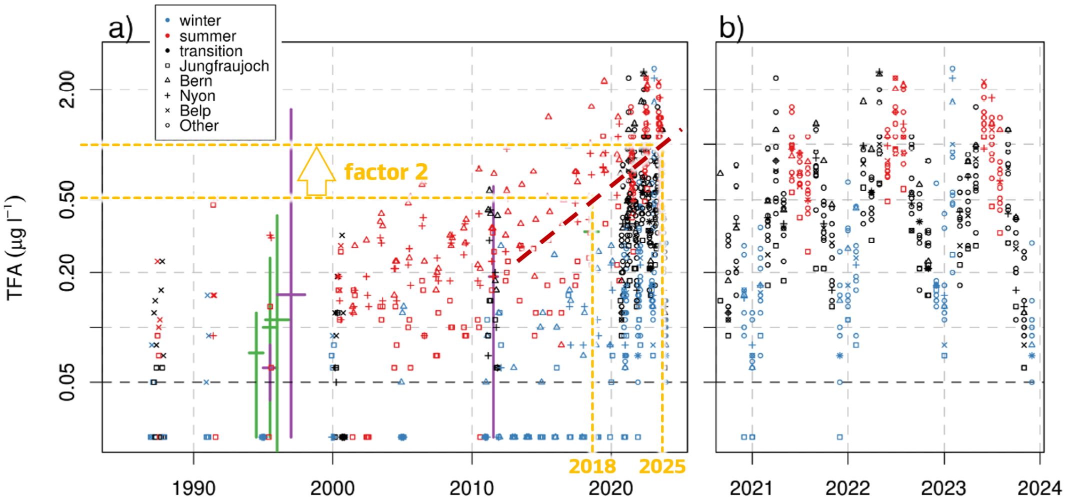


Figure 4-2: Monthly mean TFA concentrations in rainwater based on archived precipitation samples a) and recent monitoring b) at various locations in Switzerland by Henne et al. (2025). [11] The diagram on the left has been supplemented with a custom highlighting of the increase in TFA concentration between 2018 and 2025.

The data show a clear, increasing trend over time, even on the logarithmic TFA concentration scale. In addition, recent monitoring between 2021 and 2024 reveals a large seasonal variation between summer and winter. This may be linked to increased average pressures inside the air-conditioning systems at warmer ambient conditions. Differences in predominant wind directions between summer and winter may also play a role. This would require further investigation, but the overall trend is clear. In the past few years alone, from 2018 to 2025, the concentration of TFA in precipitation in Switzerland has doubled.

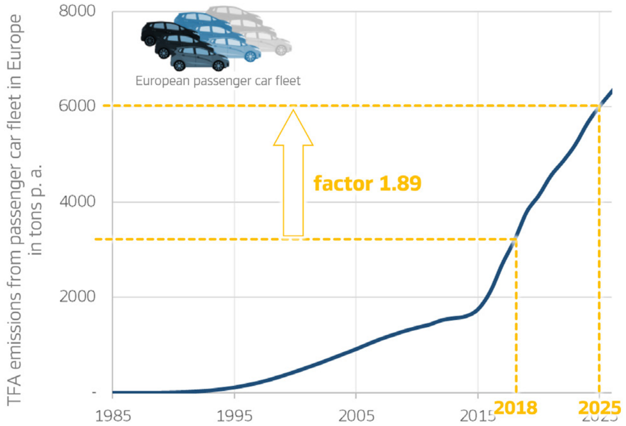
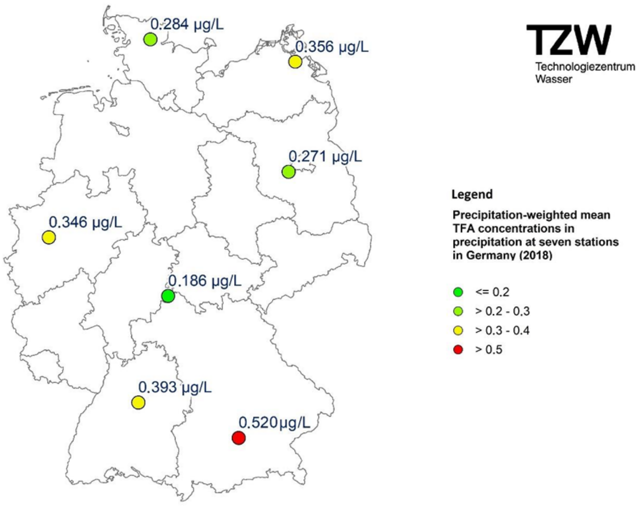


Figure 4-3: Modeled annual TFA emissions from the European passenger car fleet.

For comparison, **Figure 4-3** shows the results of the TFA calculation model presented in Chapter 3.3. During the same period, from 2018 to 2025, annual TFA emissions from the European passenger car fleet increased by a factor of 1.89. This is very similar to the increase observed in precipitation in Switzerland. It therefore appears plausible that the switch from R134a to R1234yf, together with refrigerant emissions, contributes to this strong increase.

According to various experts, TFA concentrations in precipitation are not affected by pesticides used in agriculture, since TFA itself does not volatilize and is therefore not carried from fields into the atmosphere with evaporating water. It is unclear to what extent other applications of fluorinated gases contribute to this trend, but since the transport sector represents one of the two largest areas of use for fluorinated gases, its significant impact cannot be ignored.



Source: own illustration, TZW.

Figure 4-4: Precipitation-weighted mean TFA concentrations in precipitation at seven stations in Germany (2018). [12]

Figure 4-4 shows measurements of TFA concentrations in precipitation at seven different locations in Germany in 2018. The precipitation-weighted annual mean ranged from 186 ng/l to 520 ng/l as early as 2018. [12]

In 2018, annual TFA emissions from the European passenger car fleet were about 3 200 tons/a. The peak of TFA emissions shown in Figure 3-8 exceeds 9 000 tons/a. Consequently, we expect TFA concentrations in precipitation in Germany to range between approximately 550 ng/l and 1 530 ng/l in 2036.

Another indication of the link between the transition to R1234yf and increasing TFA concentrations can be found in Figure 4-5. It shows measurements in Arctic ice cores [13] and Antarctic snow [14]. Although the distance between European cars and the North and South Poles is very large, and the polar regions are of course not influenced solely by emissions from cars, global atmospheric circulation appears to transport TFA there as well. As outlined in Chapter 2, the transition to R1234yf also occurred in other regions of the world.

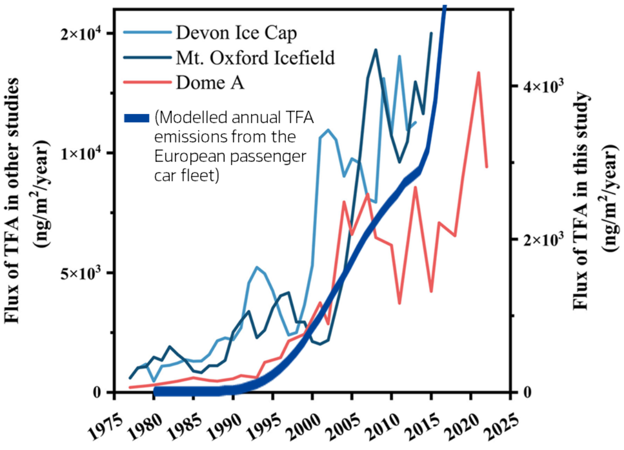


Figure 4-5: TFA concentrations in polar ice [13] and snow [14] compared with modeled annual TFA emissions from the European passenger car fleet.

4.2 Non-agricultural materials such as tree needles

One consequence of increasing TFA concentrations in precipitation could be rising TFA concentrations in plants that are not directly affected by pesticides. Figure 4-6 shows the TFA concentration measured in archived needle material from coniferous trees. [15] This supports the relationship already indicated in Chapter 4.1. Here too, TFA concentrations in needles rise in parallel with the increase in TFA emissions caused by the European car fleet. With the market introduction of R1234yf in 2017, the slope increases noticeably.

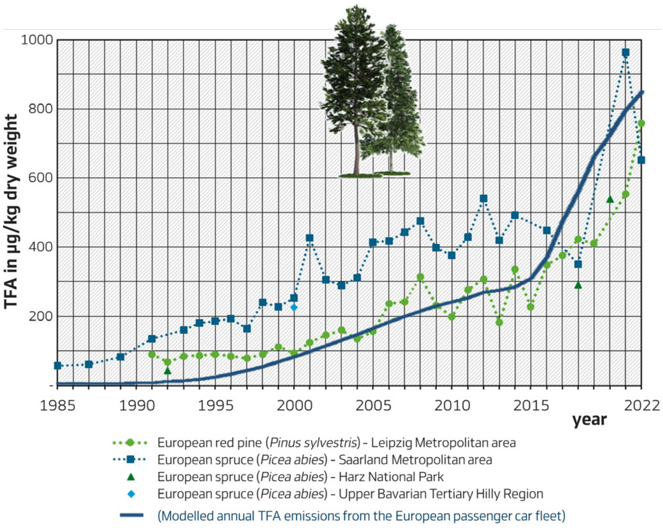


Figure 4-6: TFA concentration in the needles of coniferous trees in Germany [15] compared to same annual TFA emission curve of European passenger car fleet.

4.3 Food and beverages

In Chapters 4.1 and 4.2, the increase of TFA in precipitation and conifer needles was shown to be linked, at least in part, with the change from R134a to R1234yf in MAC systems. Could this relationship also be visible in agricultural products consumed in Europe? Because of the many influencing factors in agriculture, the causality is much more complex. Historical data are not available for most products, except for wine. Researchers analyzed wine bottles dating back to 1946 for their TFA content. [16] Results shown in Figure 4-7 again show a long period without relevant TFA concentrations, followed by a sharp increase in the last ten years as A/C systems became widespread. This may also be influenced by pesticides, but the parallel with the TFA emissions curve from MAC systems at least suggests a connection.

Other studies of cereal products in Europe show a threefold increase in TFA concentrations in the corresponding foods. [17]

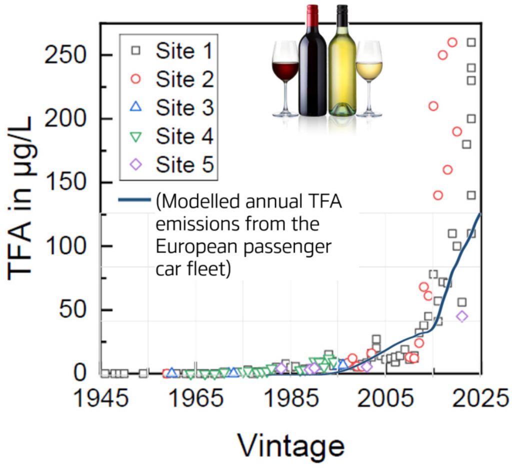


Figure 4-7: Concentrations of TFA in red, white and rosé wines from a single winery - for vintages 1946 to 2024 and for different production sites of grapes used for winemaking [16] - compared to annual TFA emission curve of European passenger car fleet.

4.4 Human blood

TFA is not only an environmental contaminant, but it is also detected in human blood. This shows that it enters the human body, contributing measurably to internal PFAS exposure. In a study of 252 adults from Tianjin, China, TFA was detected in more than 90% of serum samples, with a median concentration of 8.46 ng/ml. The authors reported that TFA was second only to PFOA and PFOS among the measured PFAS and accounted for 17.2% of the total known PFAS burden in serum. [18]

A separate study from the United States came to similar conclusions. Here, TFA was the predominant perfluoroalkyl acid in serum, with a detection frequency of 74%, a median concentration of 6.0 ng/ml, and a maximum of 77 ng/ml. In that study, TFA contributed 57% of the total serum perfluoroalkyl acid (PFAA) concentration. [19]

Similarly, European human biomonitoring data indicate that TFA is already detectable in blood and may contribute materially to PFAS internal exposure. In a Norwegian study based on serum samples collected in 2016-2017, TFA was the dominant measured fluorinated compound, with a median concentration of 6.75 ng/ml and a detection frequency of 100%. [20]

Taken together, the findings from precipitation, terrestrial environmental samples, food and beverages, and human blood point to a consistent overall picture. TFA is no longer limited to isolated environmental compartments but is detectable across multiple pathways that connect atmospheric deposition, environmental distribution, human exposure, and internal uptake. These results indicate that TFA can contribute considerably to the overall PFAS burden in humans, even though it is highly water-soluble and does not follow the classical pattern of a strongly bioaccumulative substance.

5 Effects of TFA on the human body

The exact consequences of the observed TFA levels for human health are, at present, not fully understood. Existing biomonitoring studies clearly confirm that exposure takes place. However, they do not demonstrate that the current background concentrations of TFA already lead to disease in the population at large. Cross-sectional investigations are helpful to show the presence of a substance in blood and to look for statistical correlations, yet, by themselves, they cannot prove a causal relationship. For the purposes of this white paper, it is therefore important to emphasize that a lack of conclusive epidemiological evidence for harm must not be misinterpreted as evidence of safety, especially in the case of a highly persistent compound that is already widespread in human blood.

A key mechanistic indication of possible risk is provided by a 2025 paper by Iulini et al. [21] Employing human-relevant in-vitro immune models based on peripheral blood mononuclear cells, the authors compared PFAS of different chain lengths and observed that TFA lowered antibody production to a degree similar to PFOS[14]. Concretely, both IgG and IgM levels were suppressed. These are immunoglobulin G and immunoglobulin M, the main classes of antibodies that protect the body against infections. The authors therefore concluded that carbon-chain length alone is not a suitable predictor of immunotoxicity. This insight is important, as TFA is frequently considered less critical merely because it belongs to the group of ultra-short-chain PFAS.

Although the Iulini study does not demonstrate clinical disease in humans under real-life exposure, it signals that TFA should not automatically be regarded as biologically harmless. Rather, it underlines the need for a substance-specific evaluation of TFA instead of the simplistic assumption that “shorter chain = lower risk.” Since the “TFA wave” (see Chapter 3.3.5) is still developing and the burden on the human body has only lasted ten years in this form, many potential long-term effects will only be detectable with a time lag. Unfortunately, any response would then also be significantly delayed.

Regulators are also treating TFA with increasing caution. In May 2025, German authorities submitted a proposal to classify TFA as Reproductive Toxicity Category 1B, with the hazard statement H360Df (“May cause harm to the unborn child. May impair fertility”). [22]

At the same time, the authorities stressed that this is a hazard-based classification and does not, by itself, prove that current environmental exposures are causing health damage in the general population. [23] The current official position is therefore nuanced: On one hand, TFA is considered persistent, mobile, and toxicologically relevant enough to justify stronger regulatory attention; on the other hand, available data do not yet show confirmed adverse health effects from current intake via food or drinking water.

Overall, the most balanced conclusion is that TFA is clearly entering the human body, and emerging mechanistic evidence suggests that it may have biologically relevant effects, particularly on immune function. This justifies precaution, further toxicological research, and a compound-specific approach to risk assessment.

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[14] PFOS: Perfluorooctane sulfonate, a well-known long-chain PFAS already subject to global restrictions because of its toxicity and persistence

6 Availability of Alternatives (AoA)

Thermal management without fluorinated gases

The long history of refrigerants used in mobile air-conditioning systems and the repeated changes described in Chapter 2 show that the development history of natural refrigerants in passenger cars is almost as long as the history of chemical refrigerants and their environmental hazards. Development of alternatives without fluorinated gases began as early as the end of the last century.

In the early phase, development was driven mainly by GWP rather than by the goal of avoiding PFAS, but even then, natural refrigerants and, more specifically, carbon dioxide (R744), were the key candidates for environmentally friendly vehicle air-conditioning. Based on many years of experience, Volkswagen, in collaboration with several suppliers, introduced a thermal management system using R744 on its first all-electric vehicle platform, MEB, in 2020. The system also integrated a heat pump, which is particularly well-suited to battery electric vehicles that lack waste heat from a combustion engine. In winter conditions, the heat pump significantly improves heating efficiency, helping to reduce vehicle range losses. In this context, R744 can be particularly advantageous as a heat pump refrigerant due to its favorable thermodynamic properties.

Figure 6-1: Test stands for natural refrigerant technologies at the Hanon Systems European Innovation Center in Kerpen, Germany

6.1 More than one million VW MEB vehicles with PFAS-free refrigerant

The first battery electric vehicle with a PFAS-free refrigerant entered the market in 2020 with the VW ID.3 and its R744 heat pump system. In the following months and years, this system was expanded across additional Volkswagen Group and Ford vehicles. Figure 6-2 shows a selection of battery electric vehicles that have launched since 2020, all equipped with air-conditioning and heat pump systems using R744, representing more than 1 million units in total. The vehicle program is ongoing, and production volumes are continuously increasing. In Europe, this means that in 2025 about 10-15% of newly registered battery electric vehicles are equipped with natural refrigerants. As a result, the supplier landscape for R744-specific components such as electric compressors and refrigerant valves also expanded further in 2025/26.

Passenger car thermal management systems based on PFAS-free R744 refrigerant are ready for widespread application across the MAC market, except for pure ICE vehicles. This also includes all hybrid vehicles using an electric refrigerant compressor.

Figure 6-2: A selection of battery electric vehicles built since 2020 with an air conditioning and heat pump system using the PFAS-free refrigerant R744, in a quantity of more than 1 million units.

6.2 Thermal management with R290

In addition to decades of development experience with R744, Hanon Systems is also developing and optimizing systems and components for another PFAS-free refrigerant option, namely R290 (propane). Due to its flammability, this refrigerant was not initially considered during the early development phase of natural refrigerant systems for MAC applications. As a result, this solution is at an earlier stage of development compared to R744, but it remains a valid natural refrigerant option.

To overcome R290 flammability concerns, components utilizing this natural refrigerant limit the refrigerant volume, keep evaporation in heat exchangers outside of the passenger compartment, and include special safety measures to mitigate risk in the event of a crash. These criteria support the decision to install R290 in a compact module, as shown in Figure 6-3, in the engine compartment and to distribute heat to the cabin and cooling module via additional glycol circuits. Owing to the required number of circuits, these concepts are referred to as dual-loop or tri-loop systems.

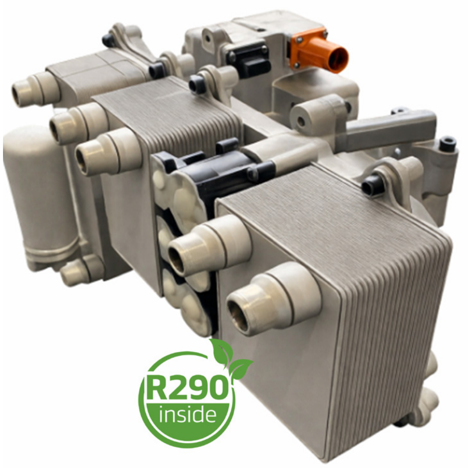

Figure 6-3: R290 Thermal Management Module, refrigerant side

Hanon Systems began building R290 test vehicles in 2023, carrying out extensive vehicle testing in-house in wind tunnels as well as under hot and cold real-world ambient conditions in Spain, Sweden, and Finland, as shown in Figure 6-4. The thermal management system with R290 was successfully tested under both extreme and moderate conditions between -35 °C and 45 °C during real driving and battery-charging processes. The R290 system was driven by an electric scroll compressor as seen in Figure 6-5.

Figure 6-5: Electric Scroll Compressor for R290 refrigerant, suitable for A/C and heat pump applications

Figure 6-4: Vehicle-level R290 testing under hot and cold ambient conditions in Sweden, Spain, and Finland.

The secondary loop design requires additional heat exchangers and causes extra temperature differences and increased pressure ratios compared to conventional R1234yf systems, as in Figure 6-6.

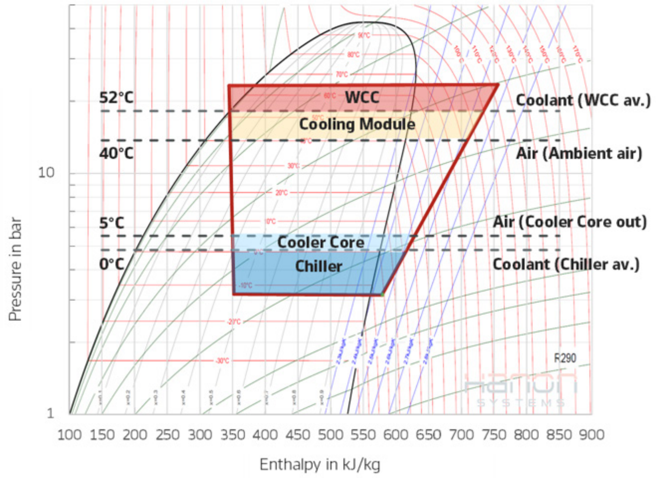

Figure 6-6: R290 log p-h diagram of a secondary loop system, illustrating pressure and temperature differences to be overcome for a typical summer use case

These additional heat exchangers, such as a cooler-core chiller, as shown in Figure 6-7, and the glycol cooling circuit, create greater thermal inertia than direct systems, which reduces dynamic performance during pulldown and heat-up. To reduce this effect, the coolant volume is minimized, and system performance is maintained through optimization measures such as vapor injection and improved heat exchangers.

In this way, secondary-loop systems with R290 can achieve the current requirement of +3 °C evaporator air-outlet temperature in pulldown mode. In heating mode, system dynamics can be improved further by hot-gas bypass. In all cases, the system is faster than most heating systems in today’s combustion-engine vehicles.

Figure 6-7:
R290 Chiller

To minimize thermal mass and inertia – as well as to minimize potential leakage risks and maintain the required charge volume – R290 is ideally integrated into a compact module, as seen in Figure 6-3 and 6-8. By integrating all refrigerant components into a single compact module, these products offer the added benefit of potentially being delivered pre-charged to the vehicle assembly line, simplifying the vehicle production process.

In summary, Hanon Systems' intensive vehicle-level investigations of the R290 system show that this PFAS-free refrigerant is also suitable for thermal management of battery electric vehicles, including battery conditioning. A potential start of production with key R290 components is planned for 2029.

The extent to which R290 is suitable for use in vehicles with hybrid drive systems would still need to be investigated within extended safety concepts, as the proximity between the flammable refrigerant and the hot surfaces of an internal combustion engine represents an additional hazard source.

Figure 6-8: R290 Thermal Management Module, coolant side, and key sub-components

6.3 R744 thermal management systems – next-generation

Over the last six years of series production of its R744 components, Hanon Systems has gained extensive experience from real-world applications with thousands of end customers in different regions. Now, these insights are being leveraged to further develop and simplify the R744 thermal management system as well as individual components – leading to improved performance and cost reductions.

Featuring design improvements honed over years of serial production and engineering efforts, the company's R744 electric compressor (**Figure 6-9**) has undergone functional optimization, design simplification, and improvements in production processes. For example, the internal control system was drastically simplified to improve both part costs and weight. Because of the R744-specific large difference between discharge and suction pressure, the scroll compressor requires a more sophisticated control of internal backpressure for its axial compensation system. At the start of production, the compressor used a so-called backpressure control valve consisting of 17 separate parts. During the optimization phase, the number of parts was reduced to five, while the functionality was even expanded. For the end product, these improvements resulted in a cost reduction of more than one third, significantly reducing the cost delta of the PFAS-free variant compared with the conventional solution using chemical refrigerants.

In addition to the electric compressor, other R744-specific components have also undergone significant improvement in recent years, such as ERVs[15], heat exchangers, and AccuIHX[16]. As a result, the cost difference between the PFAS-free solutions and the R1234yf-based solutions has become small.

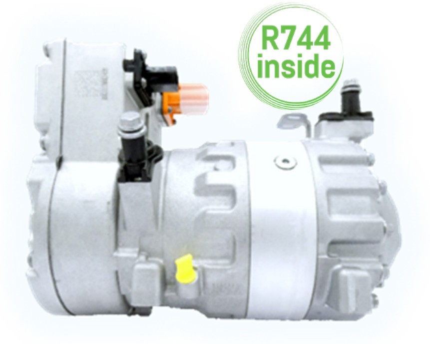

Figure 6-9: First R744 electric compressor used in VW MEB applications

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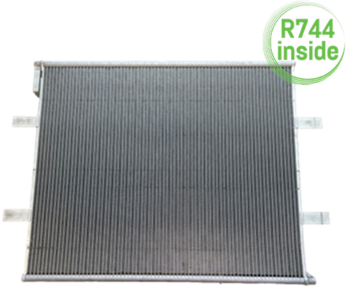
[15] ERV: Electric Refrigerant Valve

[16] AccuIHX: Combination of an accumulator and the internal heat exchanger in one component



Gas Cooler

One of the heat exchangers, the R744 outside gas cooler is essential to exchanging thermal energy with ambient air. In A/C operation mode, it ensures optimal system performance and efficiency by cooling (condensing) the R744 close to the ambient temperature. In heat pump mode, it functions as an evaporator, allowing the R744 to absorb heat from ambient air.

Accumulator

The R744 accumulator is essential for protecting a vehicle's A/C system, acting as a filter to block moisture and impurities, while ensuring the compressor and components run smoothly. It separates R744 refrigerant into liquid and gas, preventing liquid from damaging the compressor, and stores refrigerant helping the system maintain optimal performance across a wide operating envelope.

Refrigerant Valves

Refrigerant valves are a key component in a climate or heat pump system that enable activation/de-activation of heating and cooling functionality by switching between modes or expanding the refrigerant. They are proven to work with both R744 and R290.

Hanon Systems offers many key components for passenger car thermal management systems utilizing both R744 and R290. All these components (shown in Chapter 6) are ready for use in next-generation thermal management systems that rely on PFAS-free refrigerants such as R744 and R290, helping to cut future TFA emissions from the vehicle sector.

Further production increases are essential to reduce costs and finance the substantial development effort required for this innovation. All new technologies need this initial phase to minimize costs. Given the avoided contamination of food and drinking water by TFA, this initially small price difference seems easily justifiable, especially when considering the broader societal costs such as water treatment and healthcare.

7 Global view on fluorinated gases and TFA

The history of fluorinated gases described in Chapter 2, together with the many sources cited in this paper, shows that increasing TFA concentrations are truly a global issue. Because of the global structure of the automotive industry, regulatory developments in one region influence others as well.

At the same time, the relationship considered here between emissions of fluorinated gases from air-conditioning systems and TFA concentrations in precipitation makes it clear that this problem is linked especially to regions with large vehicle populations, such as Europe and China. Countries bordering oceans may experience this effect with a time lag, because depending on the prevailing wind direction, a larger share of atmospheric degradation products may be transported over the sea and deposited there.

Regulatory activity on this topic can clearly be observed in the EU, and China is also encouraging the use of natural refrigerants, especially for battery electric vehicles, from July 2029. In the USA, certain states are working on PFAS-related regulations, although TFA is not uniformly classified as a PFAS there.

Figure 7-1: A test vehicle utilizing a R290-based thermal management system at the Hankook Tire Technotrac in Ivalo, Finland

8 Conclusions

Taken together, the available evidence shows a clear overall picture. TFA concentrations are increasing in several environmental and human-related matrices, and this development runs in parallel with the growing use of R1234yf in mobile air-conditioning systems. Hanon Systems' fleet-based emissions model further shows that, without timely regulatory or technical action, mobile refrigerants will remain a significant long-term source of TFA emissions in Europe.

This is especially relevant because the problem is cumulative. Once emitted, fluorinated refrigerants can form TFA in the atmosphere, and this TFA is then transferred into the water cycle by deposition. Delayed action today therefore leads to a higher long-term burden tomorrow.

Applications of fluorinated gases are identified in the EU ECHA dossiers as major contributors to PFAS/TFA emissions. While non-automotive applications have already started to move towards natural refrigerants under F-Gas regulation, the automotive sector should now follow in order to reduce the potential health risks associated with TFA in drinking water and food.

PFAS-free alternatives are already available. Hanon Systems has developed solutions based on natural refrigerants such as R744 and R290. In the case of R744, these systems are already in use in more than one million passenger cars on the roads today. The company is highly motivated to support global automakers in phasing out PFAS-containing chemical refrigerants with these solutions.

From our point of view, this gives a clear direction for the passenger car sector. New vehicle platforms, and especially new battery electric vehicle concepts, should use PFAS-free refrigerants. A timely transition would support future regulatory compliance and help to reduce long-term environmental and health-related risks associated with TFA.

Figure 8-1: Test vehicles utilizing R290 and R744 thermal management systems perform real-world, cold climate testing in Finland

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Annex

TFA Model assumptions and input data

ASSUMPTION 1: VEHICLE FLEET SIZE AND AVERAGE VEHICLE LIFETIME

The model uses a stock-turnover approach to calculate the size and renewal dynamics of the vehicle fleet over time. It combines annual new passenger car registrations with the total number of passenger cars on the road. ACEA registration data are used to describe how many new vehicles enter the fleet each year. Because reliable and comprehensive regional data are available, the model's geographic scope is set to the EU member states, the EFTA countries, and the United Kingdom. In addition, ACEA fleet data are used to describe how many vehicles have been in use each year, as shown in Figure A-1. [24, 25, 26, 27]

Based on these two values, an average vehicle lifetime within the geographical scope is derived for each year. This annual average lifetime is then used as a practical approximation of fleet replacement. The model therefore does not use a detailed survival curve for each individual vehicle group. Instead, it uses a transparent fleet-level approach that is suitable for scenario comparison.

To reflect the demographic situation in Europe and to avoid overestimating future market growth, new registrations from 2027 onward are assumed to decline by 1% per year, based on the average trend of the previous five years. This results in a slight decrease in the overall market volume over time.

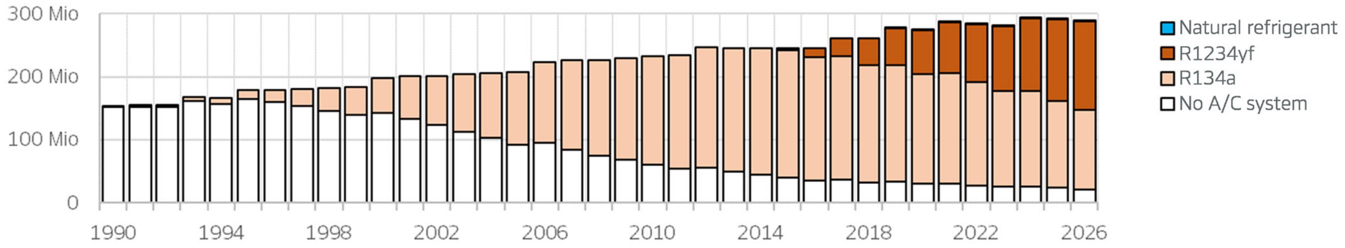

Figure A-1: European passenger car fleet size and refrigerant distribution used in the model.

ASSUMPTION 2: SHARE OF AIR-CONDITIONED VEHICLES

The model considers the development of air-conditioning and heat pump use in the fleet. Market saturation of mobile air-conditioning has developed over time, from below 20% in the early 1990s to almost 100% today, as also shown in Figure A-1. The model uses a smoothed approximation for this development based on literature and market information. This helps to avoid unrealistic step changes and gives a more realistic picture of how the relevant vehicle population developed over time.

ASSUMPTION 3: AVERAGE REFRIGERANT CHARGE

For the purposes of this model, the refrigerant charge per vehicle is represented by an average value of 500 g. This figure was determined by averaging charge data from the 20 best-selling passenger car models in Europe. [28, 29]

It is acknowledged that actual filling quantities can vary significantly depending on vehicle size, system configuration, and car manufacturer. Nevertheless, using a single representative average is a practical and transparent approach for fleet-level calculations, enabling consistent scenario comparisons without implying a level of precision that cannot be achieved. The current model does not yet account for the emerging trend toward higher refrigerant charges in heat pump systems in electric vehicles.

ASSUMPTION 4: EXTERNAL REFRIGERANT LEAKAGE RATES

The model boundary is intentionally narrow. It includes only direct refrigerant emissions from the vehicle fleet during the average vehicle lifetime. It does not include manufacturing emissions or end-of-life emissions. Refilling of lost refrigerant is not modeled as a separate life-cycle stage. Instead, the model assumes that the system is refilled during the vehicle lifetime, so that the leakage rates always refer to the nominal refrigerant charge. For systems with electric compressors, the model uses an annual leakage rate of 3% of the nominal refrigerant charge. For systems with mechanical compressors, the model uses 5% per year.

In addition, the model includes a further 2% leakage due to crash events, where the release of the full charge is assumed. These values are based on internal estimates, but they are also within a range discussed in the literature for mobile air-conditioning systems.

ASSUMPTION 5: VEHICLE POWERTRAIN TYPE SHARES

Another important input is the powertrain mix of the passenger car fleet, which is also available from ACEA. [6] The model distinguishes between internal combustion engine vehicles (ICE), hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), and battery electric vehicles (BEV). Different vehicle types are assumed to use different refrigerant compressor concepts. Internal combustion engine vehicles and 50% of hybrid electric vehicles are assigned to mechanical compressor systems. Battery electric vehicles, plug-in hybrid electric vehicles, and the other 50% of hybrid electric vehicles are assigned to electric compressor systems. The resulting powertrain mix is shown in Figure A-2.

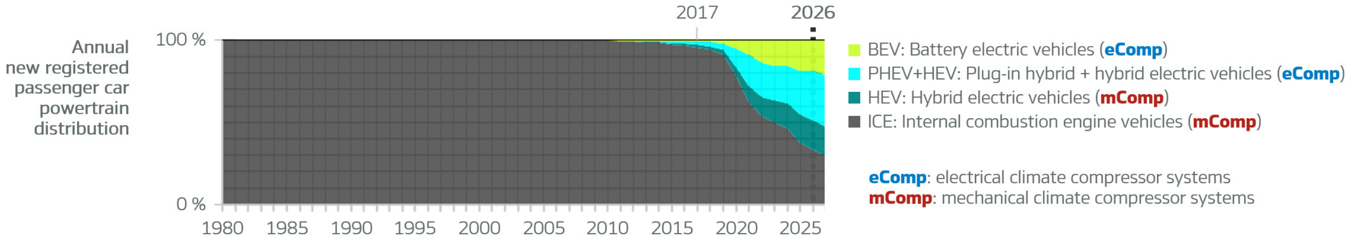

Figure A-2: Powertrain mix of new passenger cars registered in Europe annually.

ASSUMPTION 6: REFRIGERANT TRANSITIONS

The model considers the gradual transition from R134a to R1234yf in new passenger cars. Rather than assuming a changeover in a single year, the change happened over a transition period in the years prior to the R134a ban for new registered vehicles on January 1, 2017 under the EU MAC Directive. In the model, a smoothed change between 2014 and 2017 is assumed, meaning that the share of R1234yf in new cars increases gradually during these years, while the share of R134a decreases. This assumption is important because new registrations remain in the fleet for their full lifetime. The historical transition still affects emissions today, until eventually, all cars using R134a have reached the end of their lifetime (approximately 2035). These developments and their impact on the fleet are illustrated in Figure A-1.

For future years, the model changes the refrigerant choice only for newly registered vehicles, and again, existing vehicles remain in the fleet until they are gradually replaced by new vehicles. Any future ban on one refrigerant does not remove that refrigerant immediately from the market. Older vehicles continue to operate and emit refrigerant during their remaining lifetime.

ASSUMPTION 7: REFRIGERANT DEGRADATION

The model converts leaked refrigerant into TFA using the degradation processes shown in Figure 3-2. For R134a, 20% of the emitted mass is assumed to be degraded to TFA. HFO refrigerant R1234yf degrades almost completely to TFA; the model assumes a 100% yield, meaning that every kilogram of leaked refrigerant is treated as one kilogram of TFA precursor.

ASSUMPTION 8: EXISTING NATURAL REFRIGERANT FLEET

The model also considers that part of the passenger car fleet in Europe already uses the natural refrigerant R744, which is therefore not counted as a PFAS emitter. The model takes this into account by subtracting the existing R744 vehicle stock from the addressable vehicle population. For 2025, the R744 stock is assumed to be more than one million vehicles. [30] This correction improves the realism of the forward-looking scenarios.

Generally, the model is designed for transparency. Results can be traced back to a limited number of clear drivers: the number of new vehicles, the size of the total fleet, the expected vehicle lifetime, the market shares of different powertrains, the assumed compressor types, the refrigerant charge, the leakage rates, and the timing of regulatory change. It is intended to be easy to explain to non-expert readers and easy to discuss in a policy context.

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