

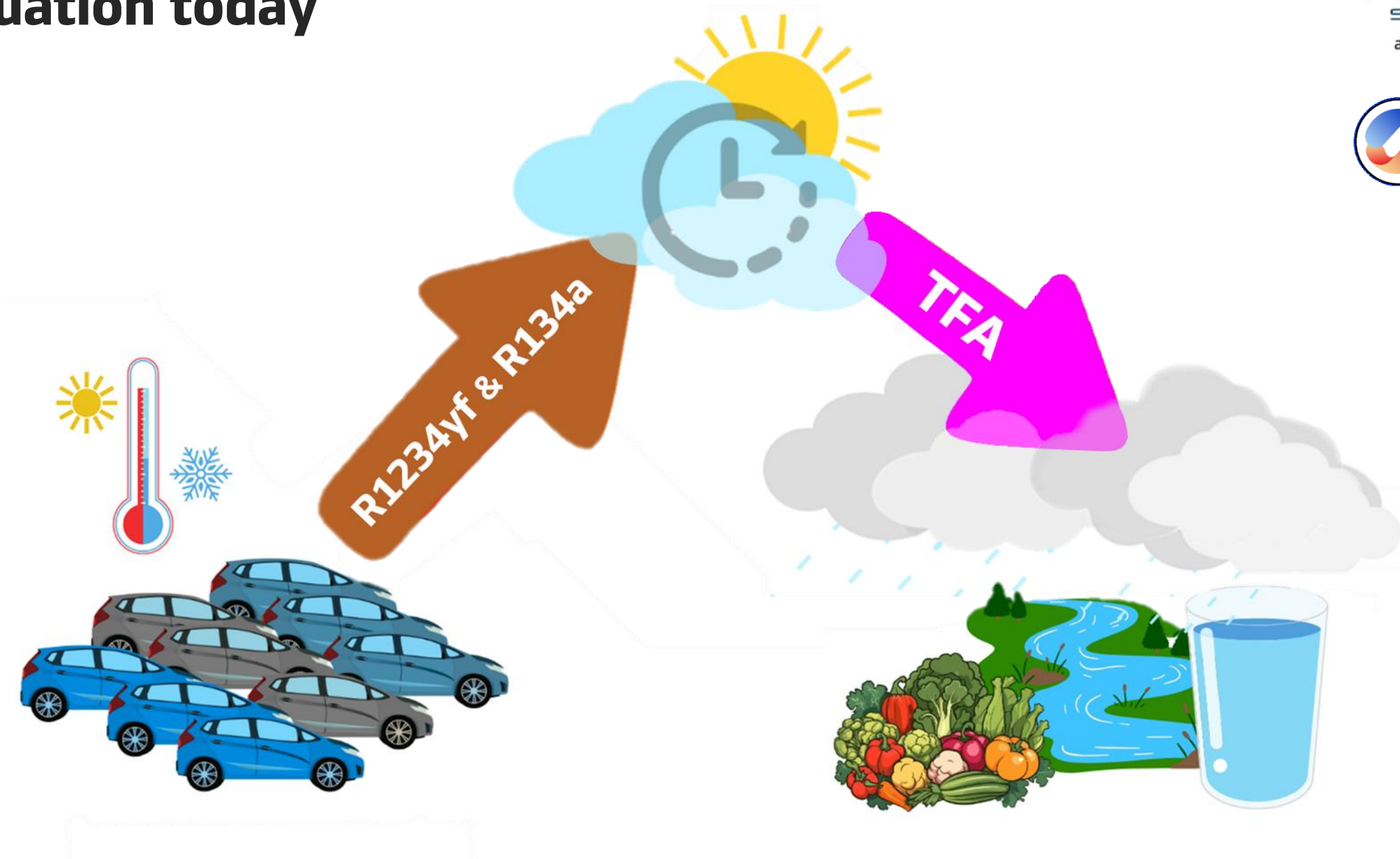


29 Sept. 2026

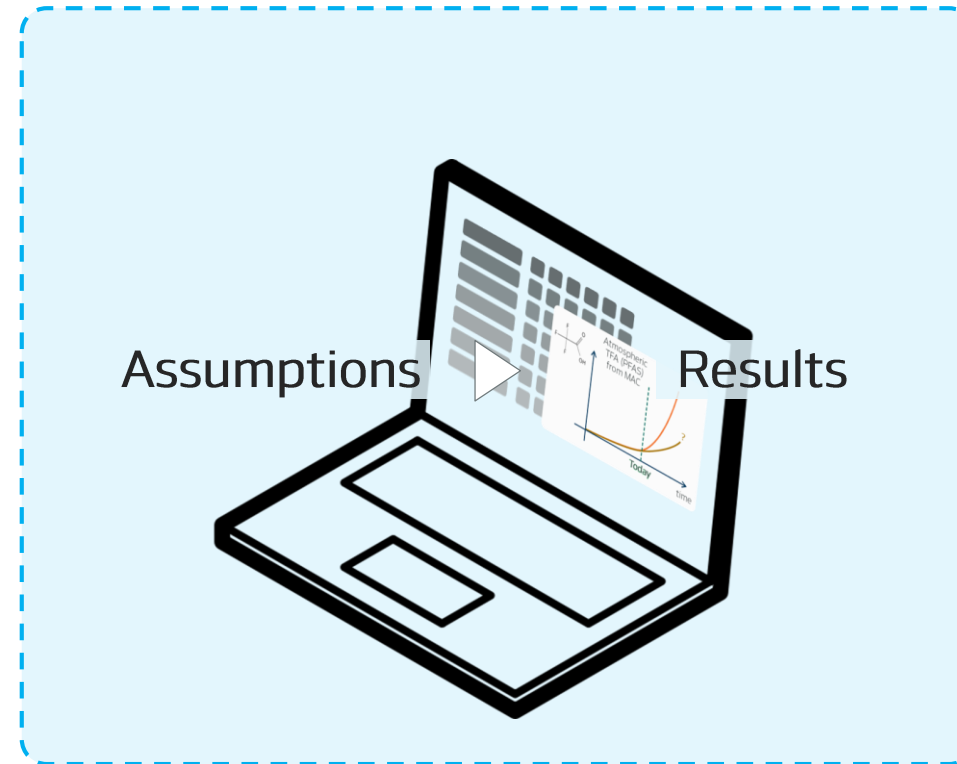
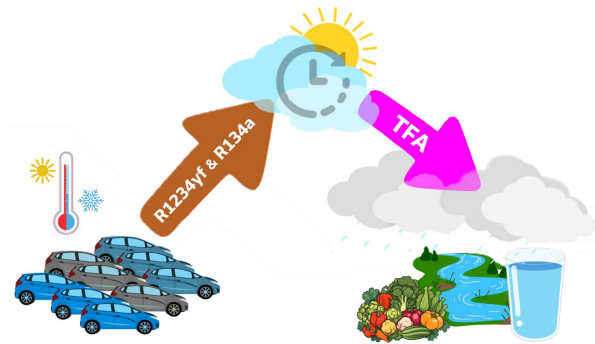
Modeling TFA Formation from MAC Refrigerant Leakage in the European Passenger Car Fleet

Henning Freitag

Situation today



Model context and objectives

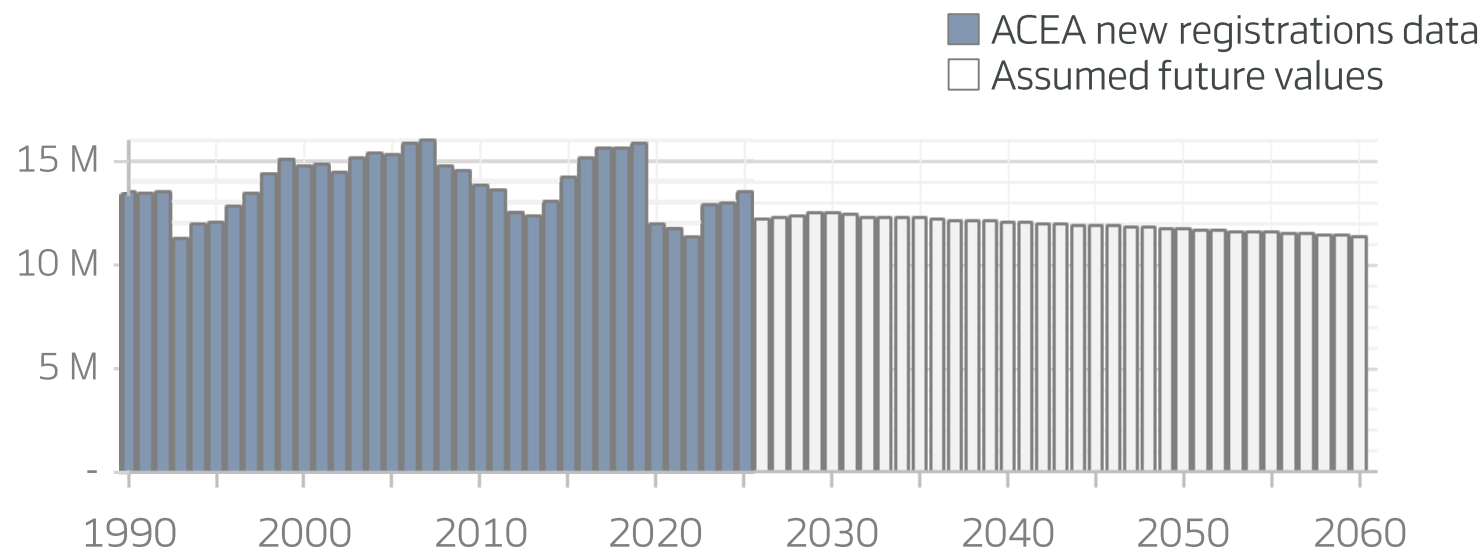


What-if analysis
▽
Impact Assessment
▽
(Decision Making)

Assumption 1/7

New registrations, total fleet size and vehicle lifetime

Passenger car
new registrations
per year
(EU+EFTA+UK)



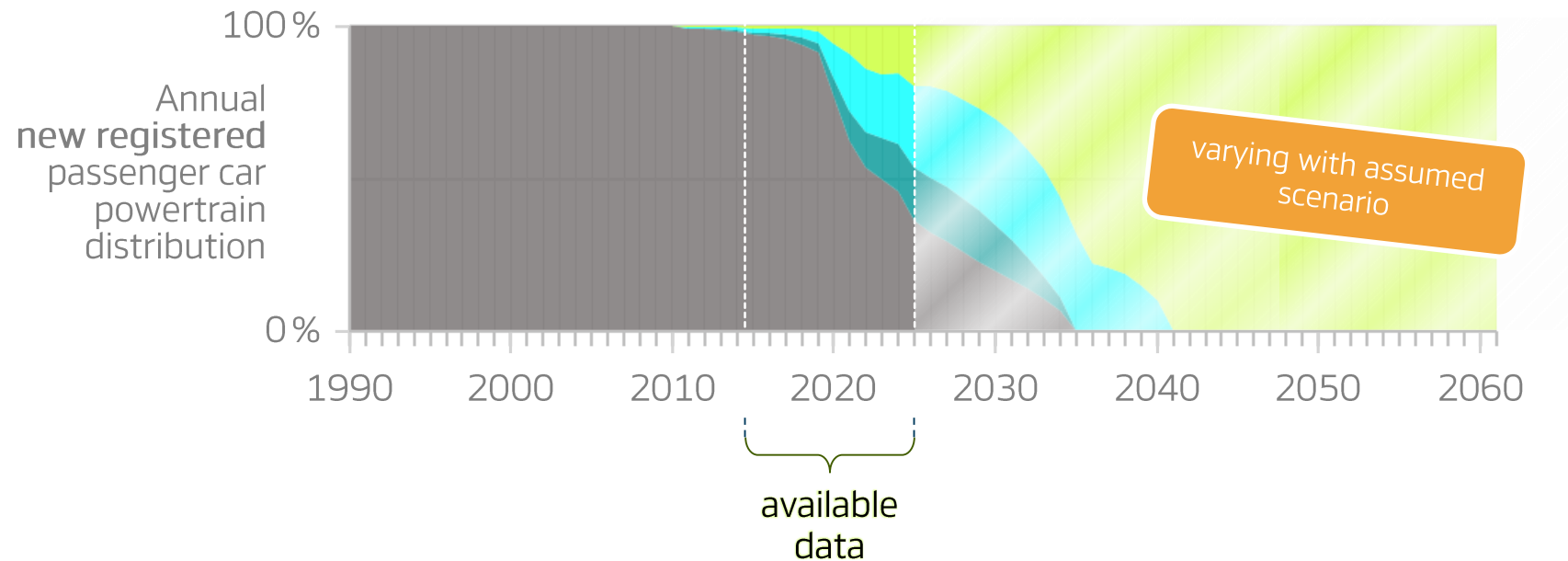
Data sources: ACEA; <https://www.acea.auto/nav/?vehicle=passenger-cars&tag=registrations-of-vehicles> | <https://www.acea.auto/figure/passenger-car-registrations-in-europe-since-1990-by-country/>
https://www.acea.auto/files/ACEA_Report_-_Vehicles_on_European_roads_2025.pdf | https://www.acea.auto/files/ACEA_Report_Vehicles_in_use-Europe_2019.pdf
https://www.acea.auto/files/POCKET_GUIDE_13.pdf | As well as other individual „ACEA Pocket Guides“ that fill data gaps. All historical data has been corrected according to the latest ACEA revision for Poland (now, only vehicles with valid road-worthiness certificate and insurance are included) Calculation is cross-checked with data sources: EUROSTAT; Road transport equipment - stock of vehicles, Passenger cars by age;
https://ec.europa.eu/eurostat/databrowser/view/road_eqs_carage/default/table | ACEA; <https://www.acea.auto/figure/average-age-of-eu-vehicle-fleet-by-country/>

Assumption 2/7

Powertrain share

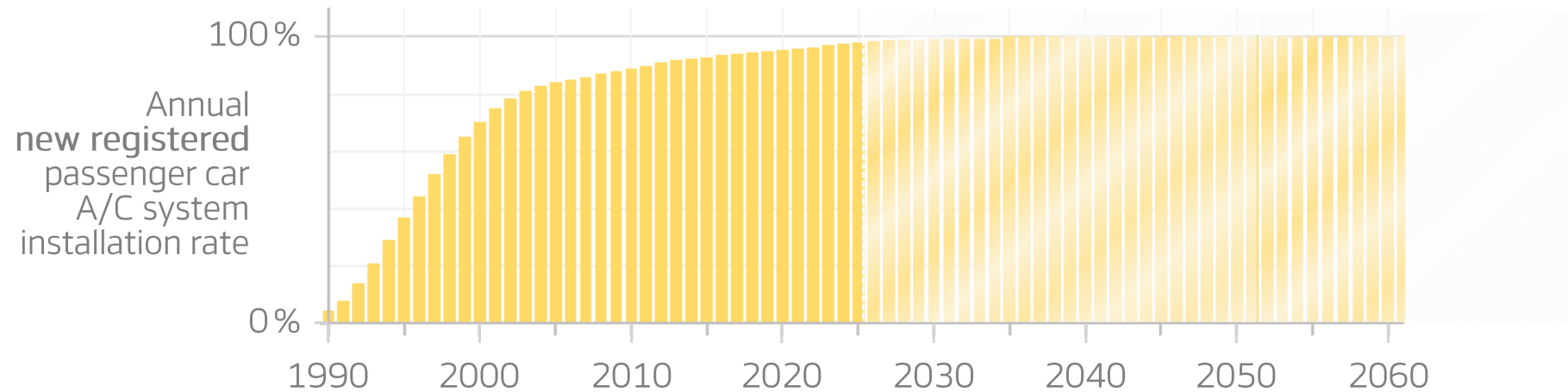
eComp: electric compressor systems
mComp: mechanical compressor systems

- BEV: Battery electric vehicles (**eComp**)
- PHEV+HEV: Plug-in hybrid + hybrid EVs (**eComp**)
- HEV: Hybrid electric vehicles (**mComp**)
- ICE: Internal combustion engine vehicles (**mComp**)



Assumption 3/7

A/C system market saturation



Data source: using own conservative curve, which is neglecting R22 share in the early 1990s, but is still similar to curve found in data sources, esp. c):

a) <https://www.ipcc.ch/report/safeguarding-the-ozone-layer-and-the-global-climate-system/> | b) <https://www.wardsauto.com/industry/europe-cools-off-ac-on-60-of-new-cars-a-big-jump> |

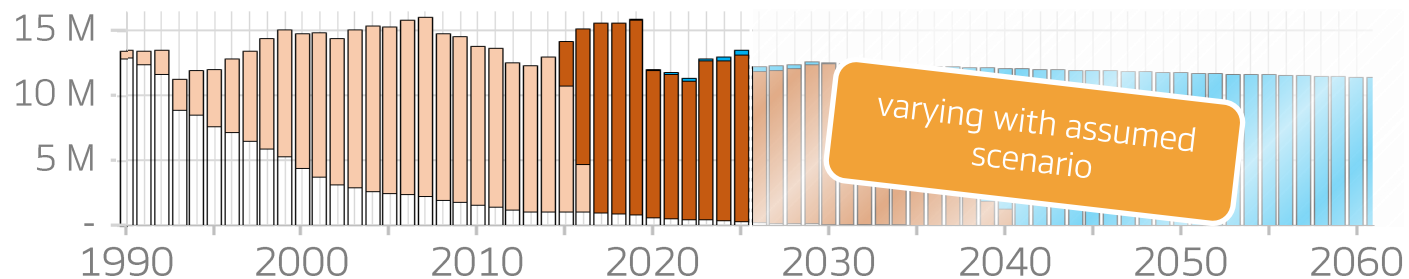
c) <http://dx.doi.org/10.2791/63451> | d) <https://theicct.org/publication/mobile-air-conditioning-the-life-cycle-costs-and-greenhouse-gas-benefits-of-switching-to-alternative-refrigerants-and-improving-system-efficiencies/> |

e) https://www.afce.asso.fr/wp-content/uploads/2024/09/Rapport_AFCE_2024.pdf

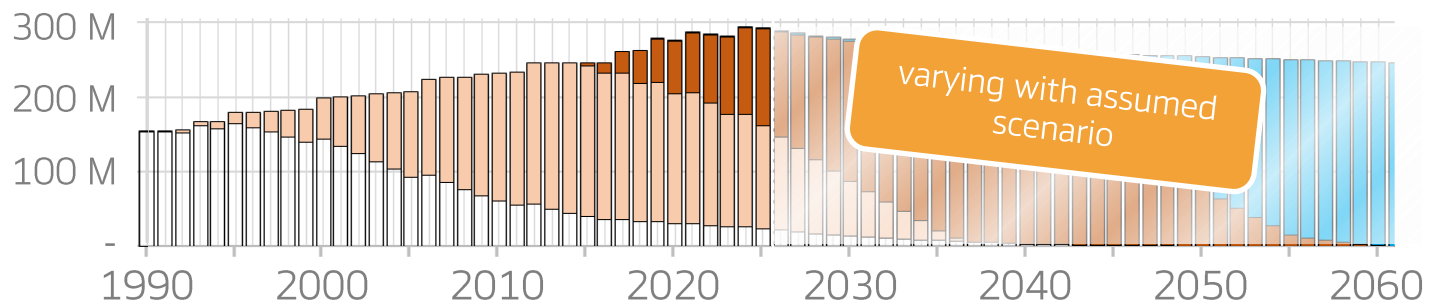
Assumption 4/7

Refrigerant share

Annual
new registered
passenger car
refrigerant
distribution



Annual
fleet
refrigerant
distribution



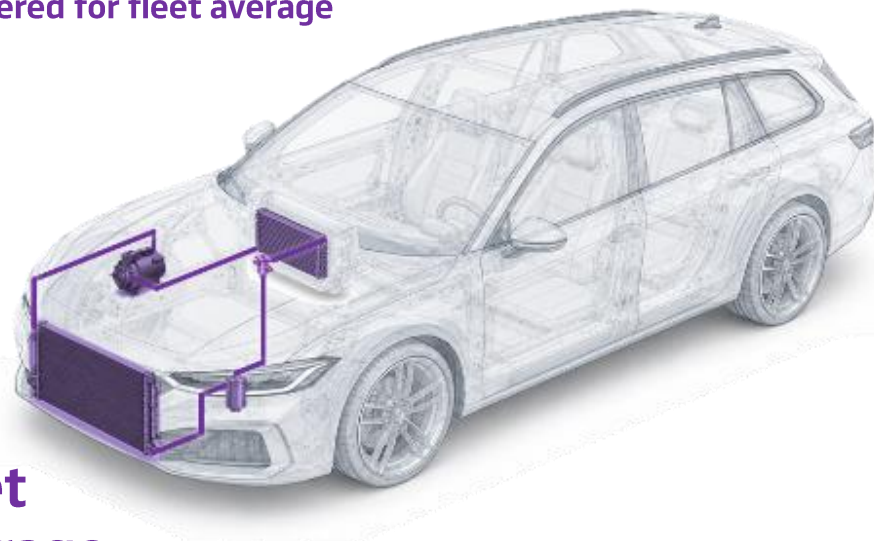
- (no A/C system)
- R134a
- R1234yf
- Natural Refrigerant

Assumption 5/7

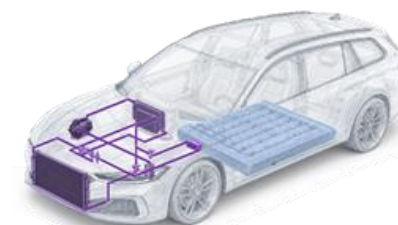


Refrigerant charge

Top20 best-selling models of
2024, 2022, 2020 and 2017 were
considered for fleet average



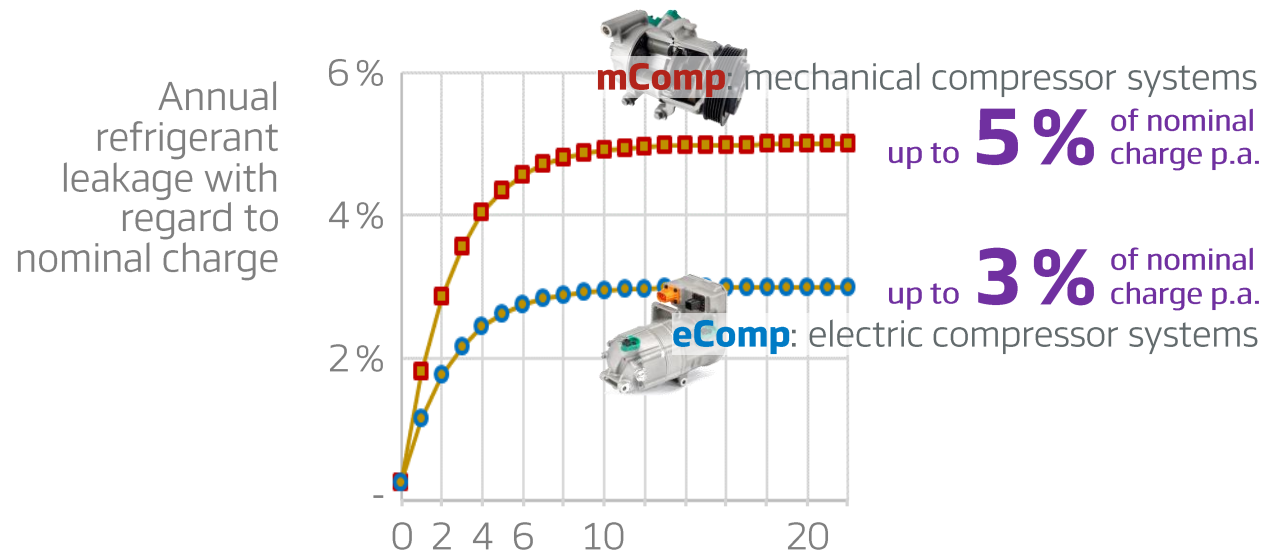
**Fleet
Average:
500 g**



(The model allows for annual
adjustments to reflect higher
charging volumes, e.g., in
heat pump systems.)

Assumption 6/7

Leakage rates

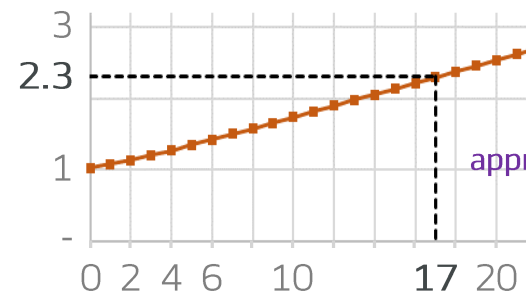


crash events

(assuming using a corresponding annual rate for 100% refrigerant charge lost in a crash event)

+ 3 % of nominal charge p.a.

Multiple of the nominal charge added to the system



fills in a 17-year old vehicle (initial fill + refills)

Data source: Own estimates, neglecting end of life emissions;

Secondary sources: (2024: 15% pre 1995, 8% post 2005) https://www.afce.asso.fr/wp-content/uploads/2024/09/Rapport_AFCE_2024.pdf

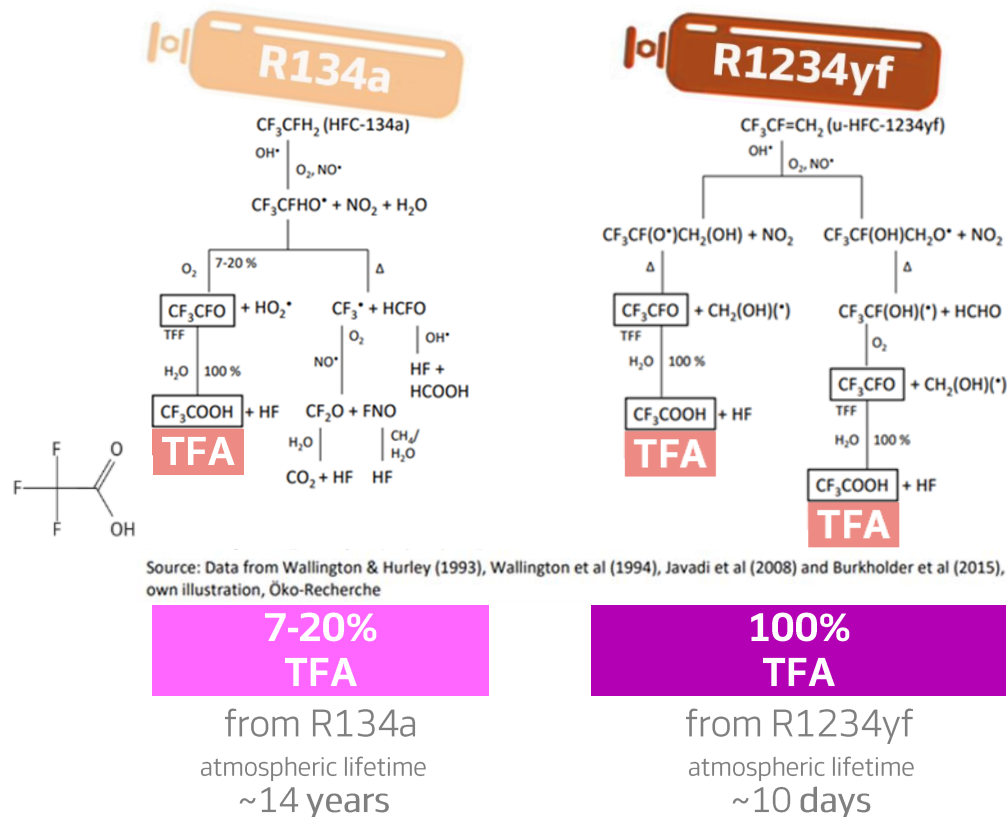
(2019: annual leakage 30 ... 40 g per year @ 480 g charge 6...8%) https://theicct.org/wp-content/uploads/2021/06/ICCT_mobile-air-cond_CBE_201903.pdf

(2003: 7,1%, EU fleet 1996-2001) https://www.oekorecherche.de/sites/default/files/publikationen/leakage_rates_0.pdf

Assumption 7/7

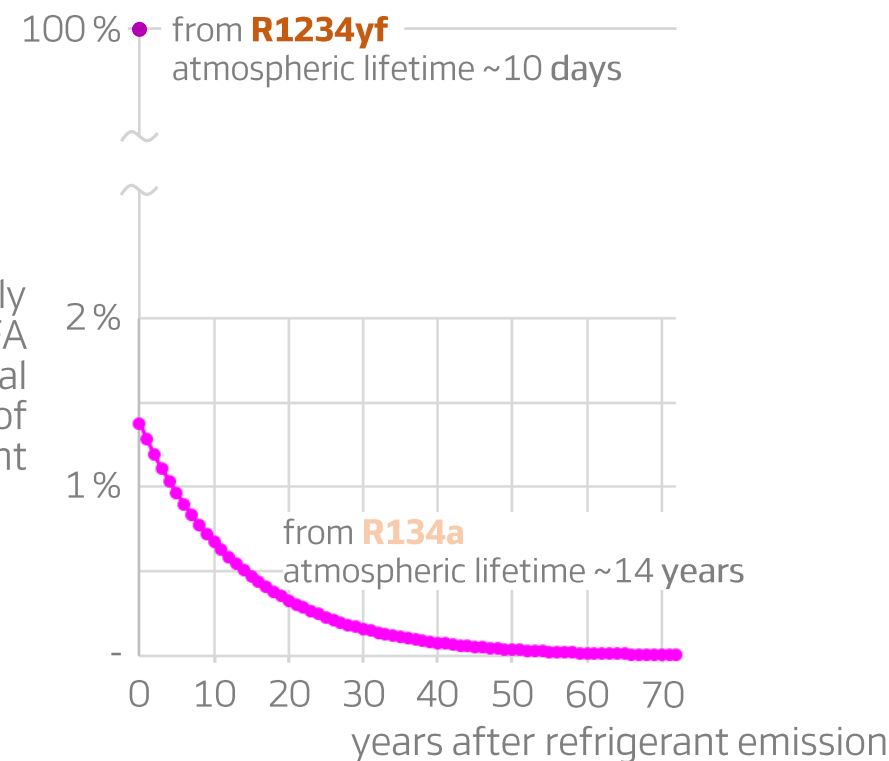
Decomposition and TFA yield

Atmospheric degradation pathways

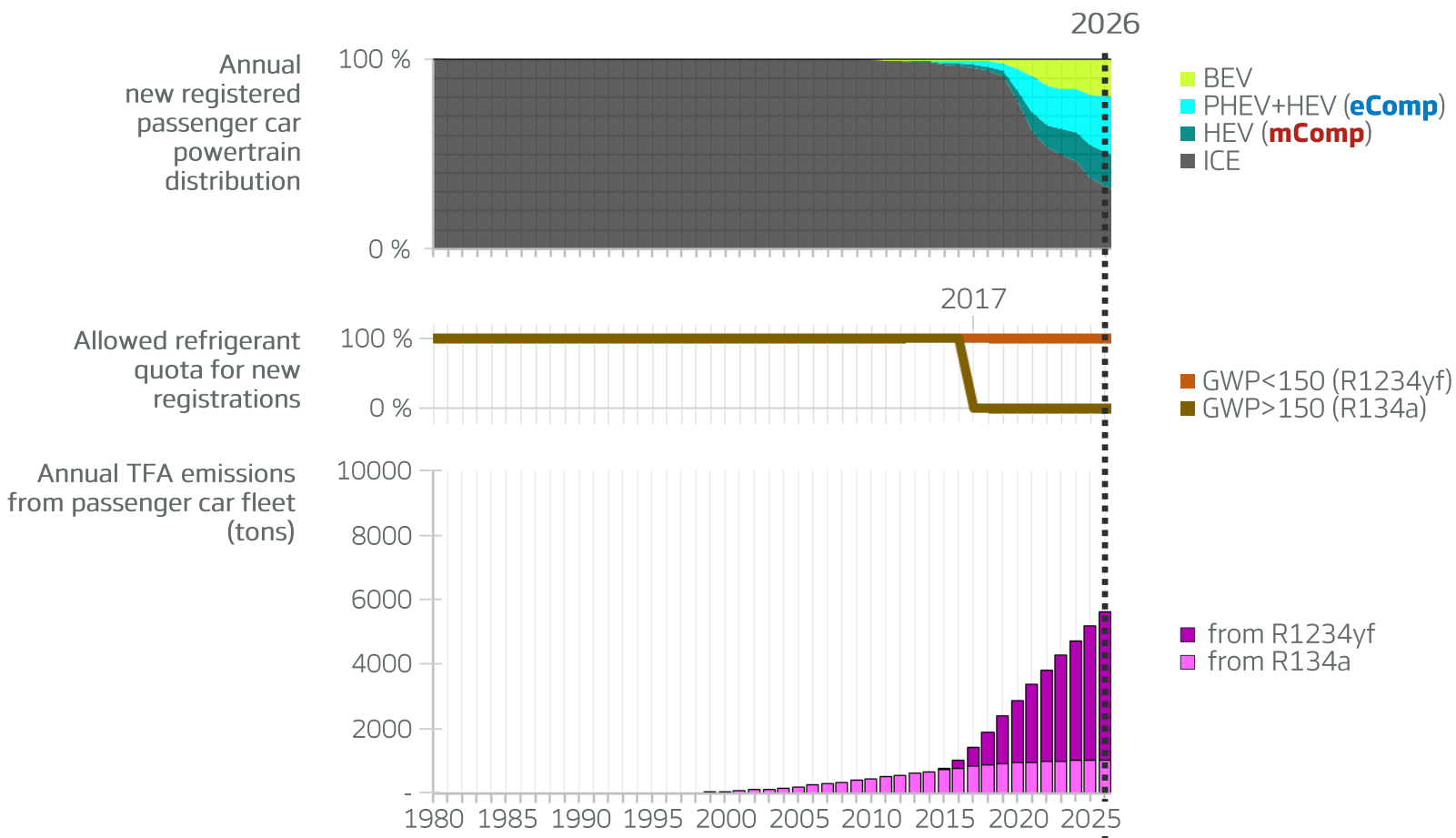


Source: Data from Wallington & Hurley (1993), Wallington et al (1994), Javadi et al (2008) and Burkholder et al (2015), own illustration, Öko-Recherche

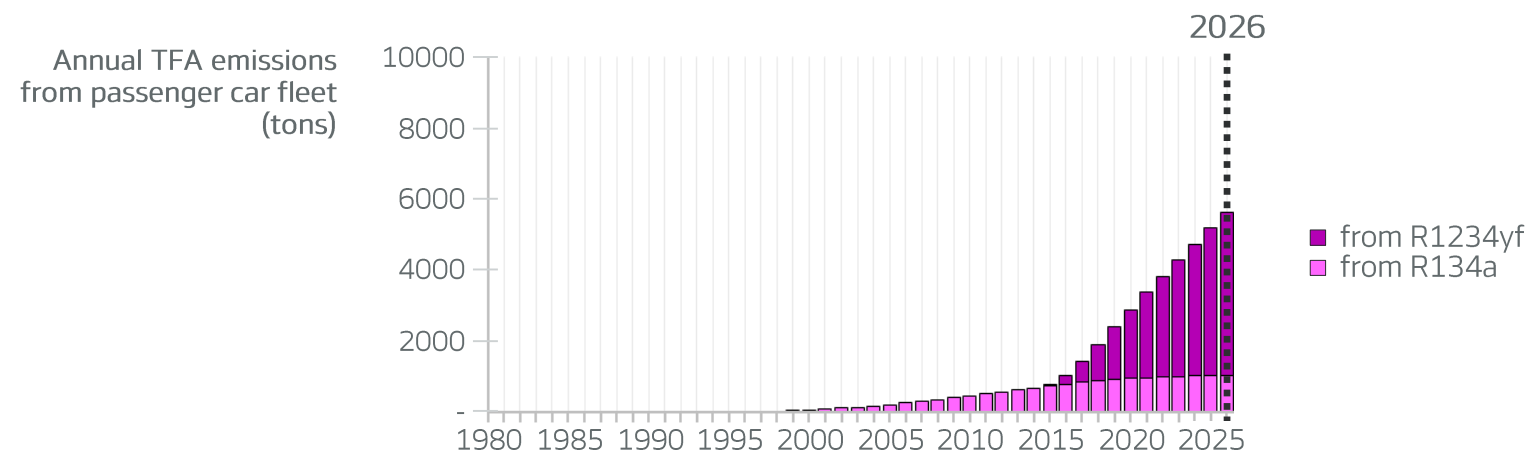
Annually
created TFA
mass / initial
mass of
refrigerant



Model results: Annual TFA emissions until today



Model results: Annual TFA emissions until today



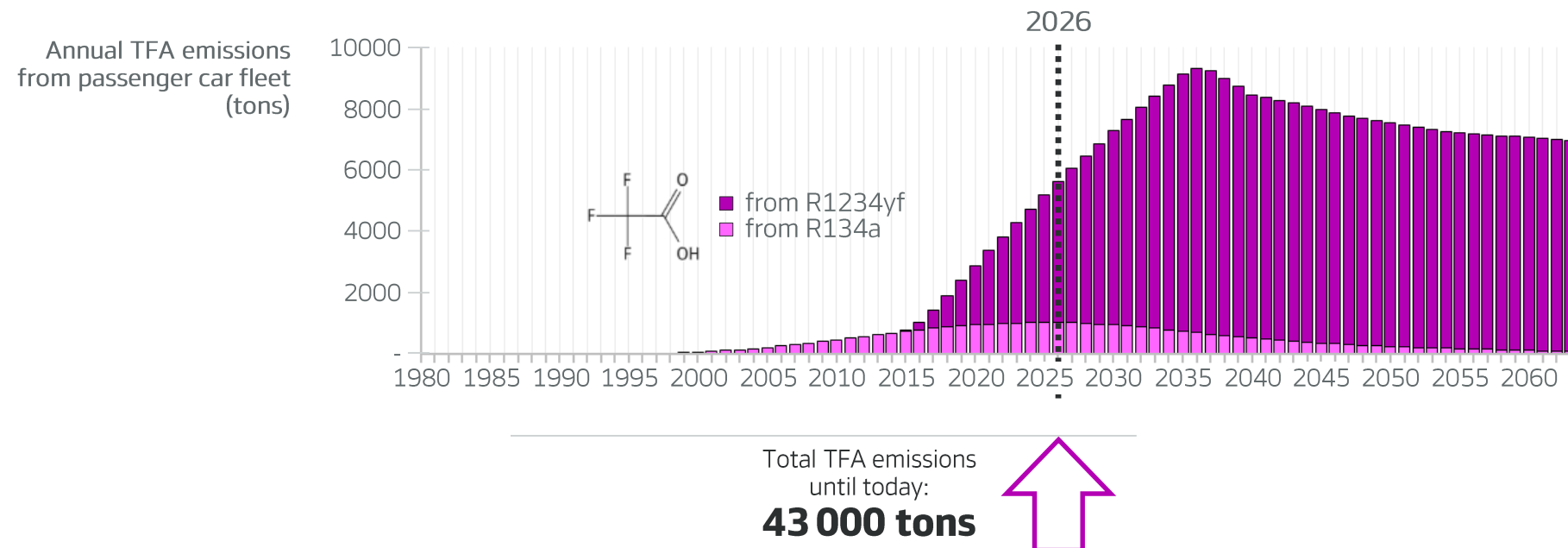
Total TFA emissions until today:

43 000 tons



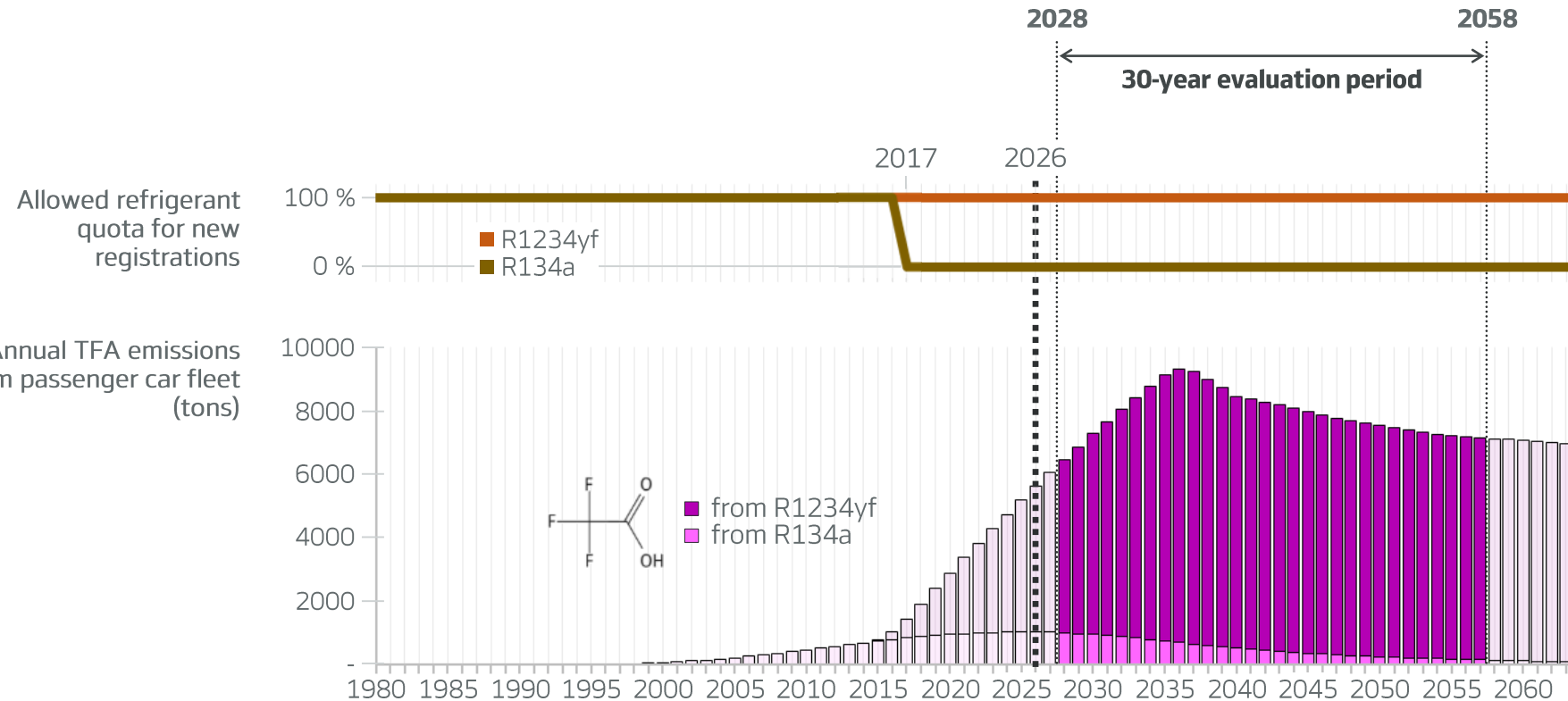
Model results: projections into the future

Scenario without PFAS regulation



Model results: projections into the future

Scenario without PFAS regulation



Total TFA emissions
until today:
43000 tons

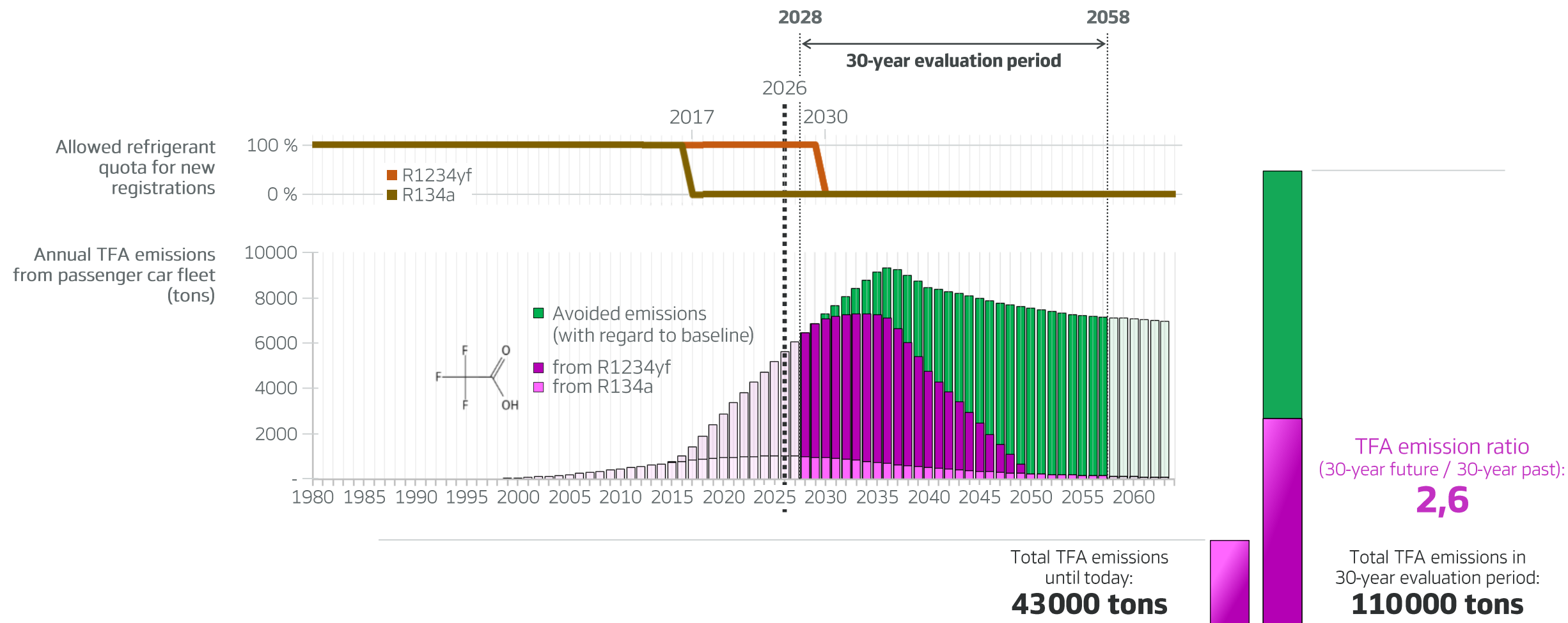
TFA emission ratio
(30-year future / 30-year past):
5,6

Total TFA emissions in
30-year evaluation period:
237000 tons

Model results: projections into the future

Scenario of Dossier submitters' RO1 proposal

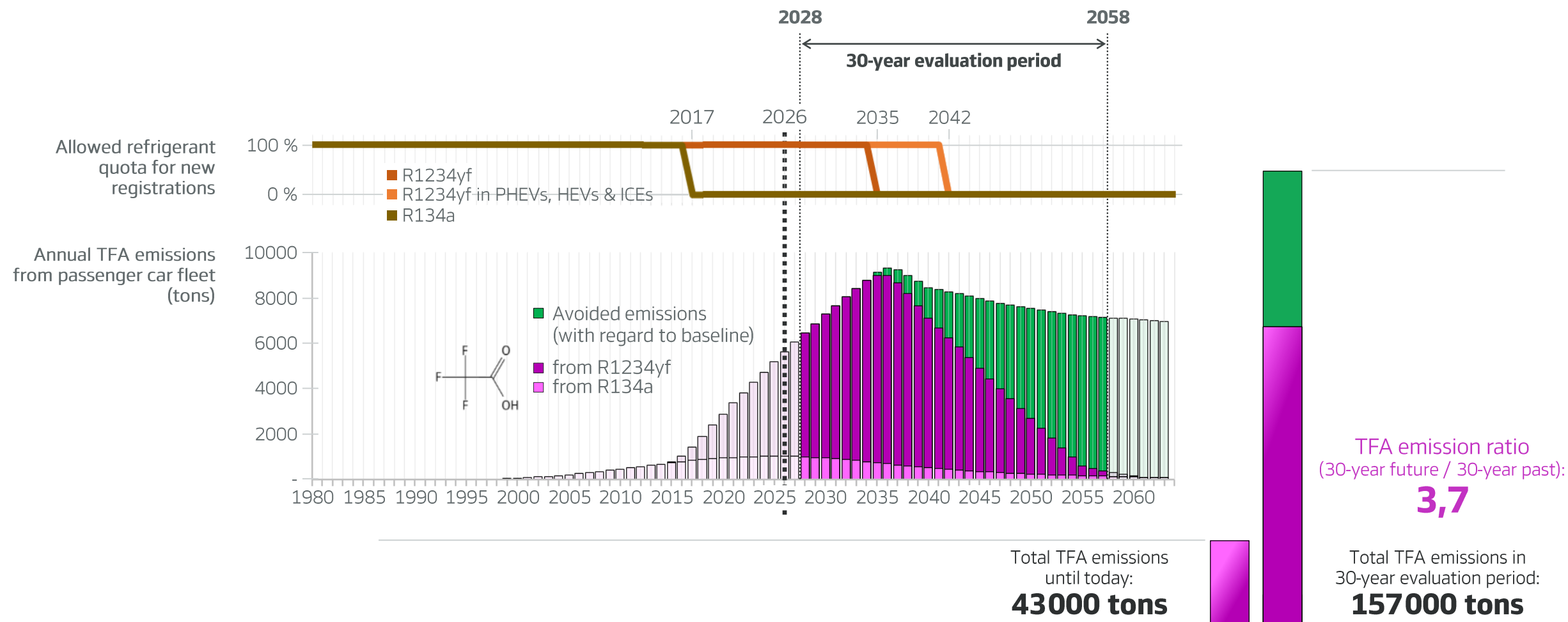
All (ICE, HEV, PHEV, BEV) 0y, assuming EiF 06/2028, transition time 18 mo.



Model results: projections into the future

Scenario of Dossier submitters' updated R02 proposal (06/2025)

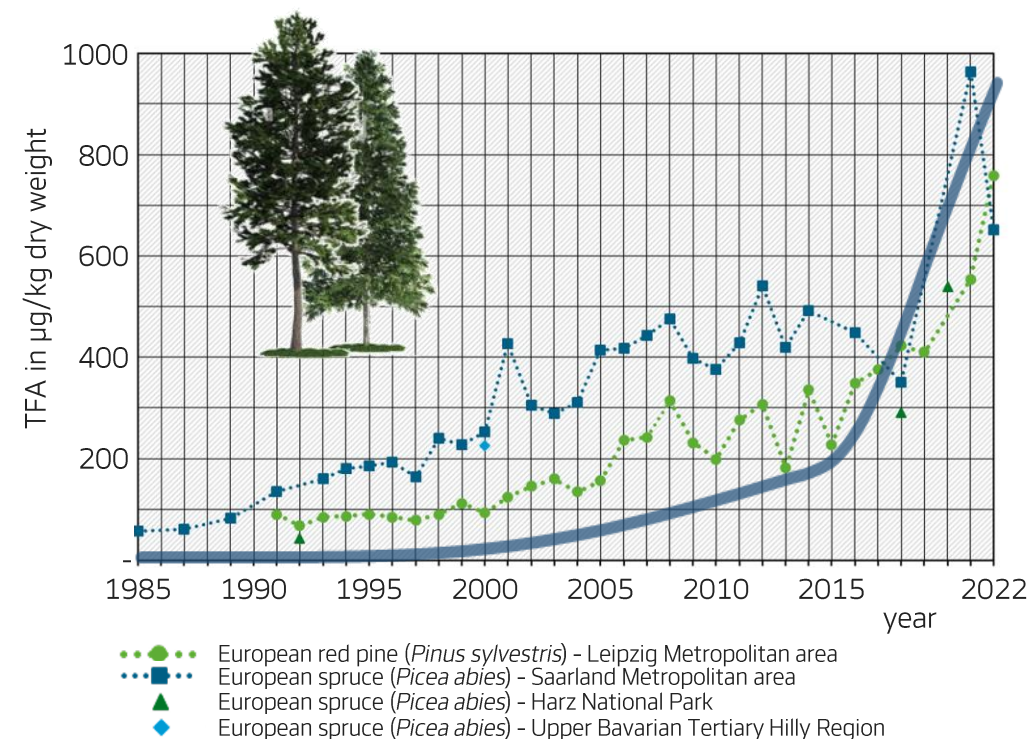
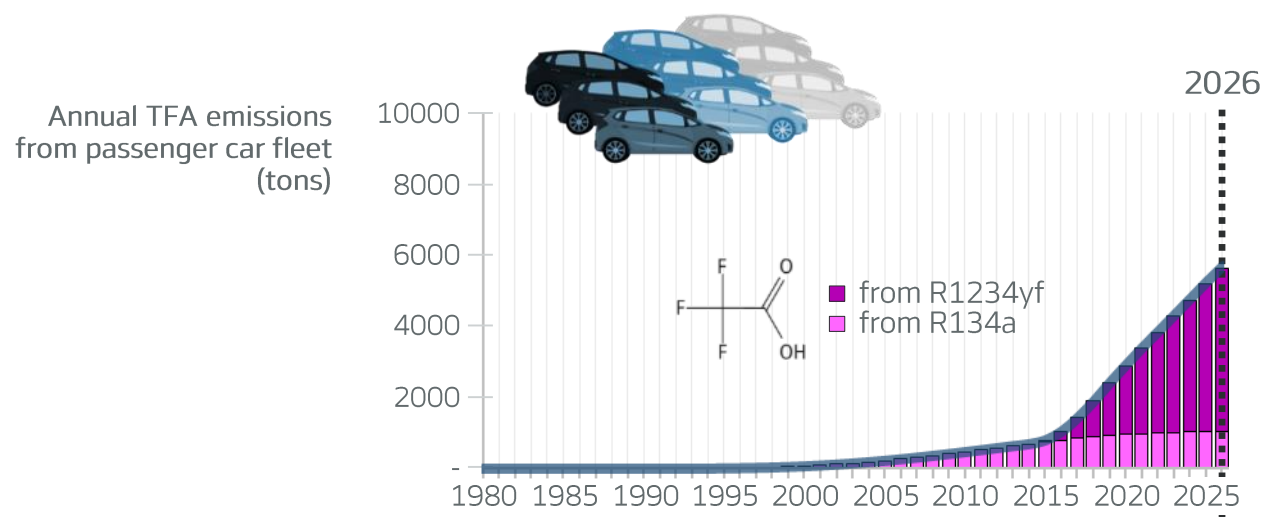
ICE, HEV, PHEV 12y, BEV 5y, assuming EiF 06/2028, transition time 18 mo.



Model results: Annual TFA emissions until today

Do we find confirmation for this trajectory in environmental measurements?

— Annual TFA load from the European passenger car fleet, calculated from the model

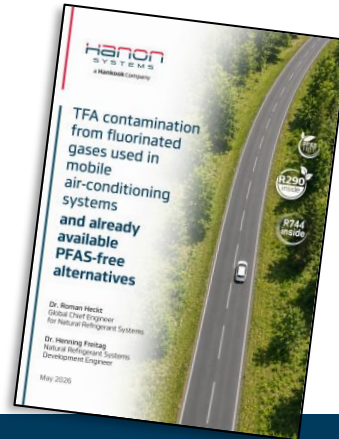


Model results: Annual TFA emissions until today

Do we find confirmation for this trajectory in environmental measurements?

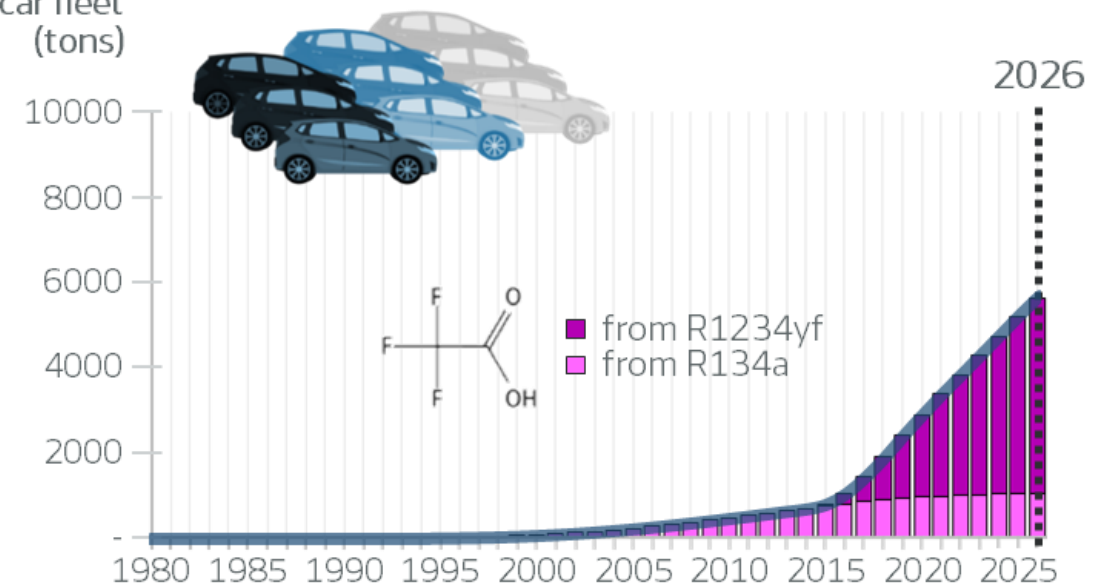
- More examples of increasing TFA concentrations are shown in our white paper for

- Precipitation in Switzerland
- Polar ice and snow
- Wine
- Human blood
- ...



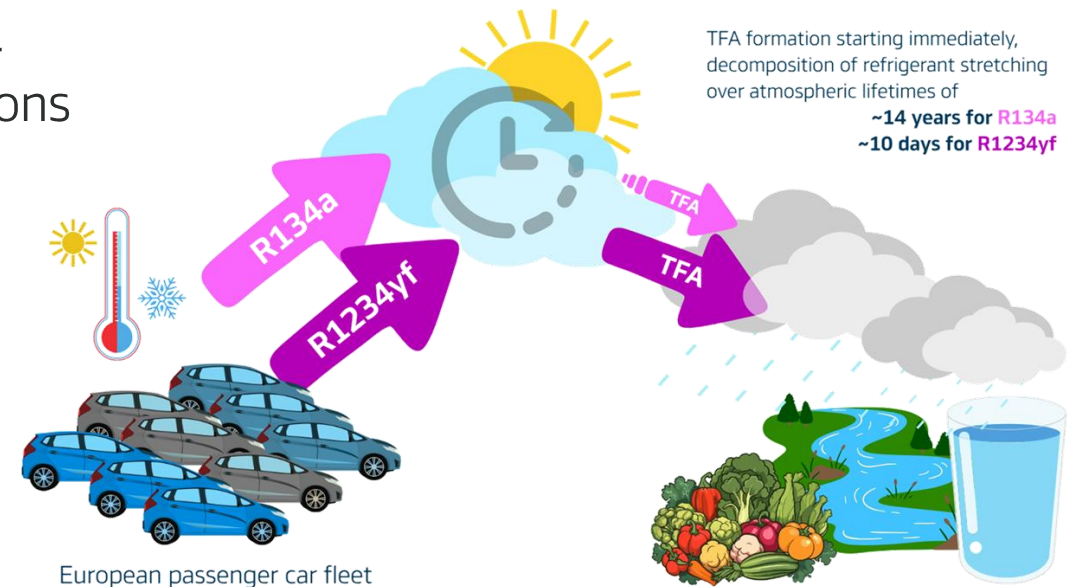
A connection between rising TFA concentrations in the environment and R1234yf emissions from the European passenger car fleet seems obvious.

Annual TFA emissions from passenger car fleet (tons)



Summary

- We developed a model aiming to assess and project atmospheric TFA load caused by passenger car A/C and HP systems in Europe
- Model projections can be made for variable input parameters, such as potential PFAS restriction EiF dates, derogation periods and scopes
- It appears that there is a correlation between our model results and the measured TFA concentrations from various institutions
- Only rapid implementation of measures will reduce a significant portion of the peak in TFA exposure that we expect to see in about 8 years
- The technology is already available (R744) or market-ready (R290)



**Thank you
for listening**
Any questions?

Enjoy reading!



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