

Lifecycle Refrigerant Emissions from Automotive Air-Conditioning Systems in the European Union

Technical Working Group

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Version 2

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Version control

Version	Author	Date	Changes
1.0	Thom Hermens, Mark Smith, Curt Vincent, MaryJo VandenBrink	April 27th 2026	Original version
2.0	Thom Hermens, Mark Smith, MaryJo VandenBrink	May 13th 2026	<p>1) Change in design leak rates to cover wider usage of heat pumps in BEVs (e.g. usage of vapor injection and higher number of joints) resulting in higher assumed design leak rate emission (e.g. introduction of heat pump for Model 1: leak rate changed from 4g/yr to 6g/yr, for Model 2: leak rate changed from 7g/yr to 9.5g/yr). Therefore, increase of overall BEV baseline with 1.75g/yr to include the addition of a Heat Pump. 2050 max leak rate as 6.5g/yr.</p> <p>2) Inclusion of reference SAE-J3267, January 2022, Automotive Air-Conditioning Service Ports Task Force Field Survey Results. Main conclusion: Missing service port caps are common, allowing debris and corrosion to impact the sealing and integrity of the port. The older the vehicle, the more likely it is to be missing service port caps.</p> <p>3) Merged inspection requirements for major service and road worthiness test. Overall, the vehicle requires an AC check & visual inspection every 2 years which needs to be demonstrated during road worthiness testing via an inspection certificate. Inspection / condenser cleaning is only required where components are easily accessible. Where components are not accessible (e.g. requires extensive part removal), relying on AC Health monitoring is compulsory.</p> <p>4) Lifetime cost information update: UV-dye inclusion <1€; AC condenser design specification <20€; AC inspection and condenser cleaning <200€; AC health monitoring <5€.</p>

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Refrigerant Emissions from Passenger-Vehicle Air-Conditioning Systems in the European Union

Baseline Assessment and Framework for Policy Scenarios (2021–2050)

Overall Introduction

The objective of setting up a technical working group on refrigerant emissions is to quantify as an industry average the refrigerant emissions in mobile applications in the various stages of its lifecycle:

- Refrigerant production
- Refrigerant delivery
- Vehicle First fill
- Vehicle design, or emissions during the normal use of the vehicle
- Vehicle repair/accidents
- Vehicle service/repair, or the emissions related to the service and repair process, not the refrigerant used to recharge the system during maintenance
- Vehicle end of life
- Refrigerant reclamation.

By gathering data throughout the value chain, an emission baseline is set (2021) and illustrative estimates provided for the upcoming 30-year time horizon of the evolution of the refrigerant emissions in the mobile air conditioning application.

These estimates can be used to build several indicative possible refrigerant emission reduction scenarios, and related policy options and determine the average emission reduction potential by 2050 over a 20-year period (2030 to 2050).

The work of the Technical Working group was initiated to support the authorities working on the PFAS restriction proposal (Dossier Submitters, ECHA and Commission), who are exploring additional measures to reduce refrigerant emissions as an alternative risk management option. Currently there is a lack of industry data available to the authorities to quantify the emission reduction potential of the measures already in place and new measures which could be implemented in the context of a REACH restriction of F-gases in the transport sector over the assessment period (2021-2050).

A pre-meeting took place on October 22nd, 2025, followed by an official kick-off of the Technical Working Group on November 5th. The technical working group gathers value chain players interested in better understanding the level of emissions in the EU and what steps have been taken and can be taken to reduce them. The working group was divided into 4 sub-groups, to tackle the lifecycle stages that represented the majority of the estimated emissions: vehicle design, vehicle damage/accidents, vehicle service/repair and vehicle end of life. Each sub-group met on a regular basis to discuss available data and assumptions and review modelling. Individual meetings also took place with value chain participants to dive deeper into specific questions or explore options before discussing with the larger group.

A status meeting was also held with the working group to update on the progress and next steps of each sub-group.

8 OEMs took part in the meetings (light vehicle producers and also heavy-duty OEMs), 6 Tier 1 manufacturers, 1 garage chain, 1 distributor, 2 refrigerant producers and 2 end-of-life actors.

Emissions Summary: Baseline, Reduction, Effectiveness

The overall refrigerant emissions across the value chain for automotive applications are summarized in the below table.

Annual refrigerant emissions [MT]	Baseline - status quo					Proposed regulatory measures		
	2021	2026	2030	2050	2030-2050	2030	2050	2030-2050
Production (not in EU)	-	-	-	-	-	-	-	-
Logistics incl. downpack (~0.01%)	2	2	3	3	63	3	2	45
First fill	8	9	9	9	192	9	9	192
Design architecture	11'652	11'570	11'505	8'851	218'892	11'307	4'726	132'612
Accidents	221	246	301	257	6'184	301	257	6'184
Repair	1'959	2'186	2'966	4'310	83'774	1'928	708	26'544
Service (recovery rate, # services)	1'110	1'626	2'595	1'804	58'416	1'770	341	19'515
End of life	27	34	48	119	1'800	48	40	816
Refrigerant recycling (~0.01%)	0	0	0	0	1	0	0	1
Total	14'979	15'674	17'427	15'353		15'366	6'083	

% change annually (vs 2050 baseline)

-12%

-60%

% change annually vs 2026

-61%

Total 2030-2050 emissions

369'322

185'909

Total reduction versus baseline (2030-2050)

-50%

The following Regulatory measures to reduce refrigerant emissions as condition of use – summary (all working groups):

Workstream	Category	Measure (Entry Into Force, Jan 1 st , 2030)	New vehicle production			Existing vehicles		Additional cost in € / vehicle lifetime	Total cost [Euro MM]	Emissions saved	Cost/kg emission saved
			ICE	Hybrid	BEV	ICE/Hybrid	BEV				
Design architecture	Design leak rates	Maximum design leak rates for new vehicle registrations, linear reduction (g/vehicle): ICE: 7.6g (2030) to 7.4g (2034) BEV: 7.5g (2030) to 6.5g (2050)	Yes	Yes	Yes	-	-	-	€0 as increased maintenance improves AC component life with 30-50% **	141k MT	€0/kg due to the increased AC component life expectancy, **
		First fill and retrofit of AC service port caps (during service) replacement with a tethered caps	Yes	Yes	Yes	Yes	Yes	<1			
Repair, accidents	Design robustness	Compliance to new condenser robustness design specification, similar to SAE J2842 (to be developed)	Yes	Yes	Yes	-	-	<20	€0 as increased maintenance improves AC component life with 30-50% **	141k MT	€0/kg due to the increased AC component life expectancy, **
	Inspection	Obligation for UV Dye inclusion, SAE J2297	First fill	First fill	First fill	At service	At service	<1			
		Compulsory for a major service (e.g. oil/break fluid change) every ~2 years: AC check & visual inspection*** (UV dye) & requirement to repair, AC condenser water cleaning & debris clearing***. Inspection certificate issue for road worthiness test inspection.	-	-	-	Yes	Yes	<200			
		Verify the AC check & visual inspection and condenser cleaning have been carried out in the last two years during road worthiness testing (verify inspection certificate).	Test at factory	Test at factory	Test at factory	Yes	Yes				
Ongoing monitoring	AC system health monitoring, according to industry design specification (to be developed)	Yes	Yes	Yes	-	-	<5				
Service / End of Life	Service/recovery machines	Recovery, Recycling and Re-charge machine, compliance to SAE J2788 & J2843, 40g to ensure repair	Yes, all recovery and RRR machines in EU					-	€89MM	38k MT	€3/kg
End of life	Traceability	Requirement for full refrigerant traceability, from first fill, service, end of life, recovery & recycle/reclaim. Requirement for recovery and recycling/reclaim at end of life (EPR)	Yes, management via refrigerant digital log-book					-	€8.6MM	983 MT	€9/kg
	Compliance with good working practices	Registration and audit of authorized treatment facilities, each country requires a registration and audit system to ensure compliance with good working practices	ICE/Hybrid/BEV								

** < €200 / existing vehicle: 259*200 = €51'800 MM; and < €27 / new build vehicle: 10.4*21*27 = €5'897 MM. Total: €57'697 MM.

Cost per kg emission saved (direct equivalent cost impact): €57'697 MM / 141k MT = €409/kg

*** Inspection / condenser cleaning where components are easily accessible. Where components are not accessible without extensive part removal, relying on AC Health monitoring is compulsory. Condenser cleaning involves a simple low pressure water spray, carefully applied not to damage the condenser fins.

Main Conclusions

- The overall emissions are reduced on an annual basis (2050) by -60% to 6083MT versus the baseline and -61% versus 2026.
- Between 2030-2050, a total amount of **183,413MT of emissions are prevented (-50% reduction)**
- Cost/kg emission saved: €57'795 MM / 183,413MT = **€315/MT**
- Since most of the regulatory measures will lead to an increased component life expectancy of +30%-50%, it can be concluded that the **net cost to consumers is €0/MT**

Production

Workstream Description, Data Set Used, Refrigerant Emissions

The refrigerant production entails the manufacturing stage of producing the refrigerant. Currently there is no refrigerant production in the EU (for refrigerants used in automotive applications) and no known plans for refrigerant production in the future. It can therefore be concluded that there are no emissions linked to refrigerant production in the EU.

Delivery

Workstream Description, Data Set Used, Refrigerant Emissions

The refrigerant delivery entails the operations to transload refrigerant from bulk storage or transport vessels to shipment vessels of different sizes. During this operation, very small quantities of refrigerant are emitted to the environment. The current technology already greatly limits the amount of refrigerant emitted allowing the different value chain players (producers, OEMs and down packers) to meet their emission permitting requirements and to reduce the loss of valuable refrigerant. Pipe vacuum operation, automatic filling stations, and the use of ultra-low emission valves allow the emissions to reach a very low level. Discussions with distributors and producers showed this is common industry practice. It is estimated that the emissions during delivery will not represent more than 0.01% of the total refrigerant annual need. This has been calculated as the total estimated refrigerant emissions + first fill needs (which is overly conservative).

Total 2030-2050	Baseline - status quo				Proposed measures	
	2021	2026	2030	2050	2030	2050
New vehicle on market [MM]	9.68	11.40	11.40	11.40	11.40	11.40
First fill logistics emissions EU MT/yr, 0.01%	0.55	0.92	1.20	1.25	1.20	1.25
Lifecycle logistics emissions EU MT/yr, 0.01%	1.50	1.50	1.70	1.40	1.50	0.50
Total logistics emissions, 0.01%	2.05	2.42	2.90	2.65	2.70	1.75

Total 20230-2050 emissions

- Without proposed measures: 62MT
- With proposed measures: 44MT

No additional emission reduction scenarios are considered for delivery (besides less overall lifecycle refrigerant emissions).

First fill

Workstream Description, Data Set Used, Refrigerant Emissions

The refrigerant first fill entails the refrigerant charging process from the OEM production facility bulk tank into the vehicle on the production line. This typically happens in one of the last production process steps on the vehicle production line. Albeit there are some different types of refrigerant

charging machines, the differences from a refrigerant emission perspective are deemed to be negligible.

Data Set

The procedure of preventing refrigerant leakage in vehicle manufacturing has been described in the 2012 JAMA Environmental Report¹, where leakage has been reduced to 0.8g per vehicle. The automakers use cutting-edge technologies to charge mobile air conditioners with refrigerant and are working to achieve further reductions in emissions leakage in future (e.g. making use of refrigerant chargers equipped with a device to recover any gas remaining in the delivery hose).

Baseline Scenario and Emission Reduction Scenarios (2030–2050)

The baseline refrigerant emissions are calculated based on the European new vehicle production numbers.

Total 2030-2050	2021	2026	2030	2050
New vehicle on market [MM]	9.68	11.40	11.40	11.40
Refrigerant emissions EU MT/yr	7.7	9.1	9.1	9.1

Total emissions 2030-2050 191.5 MT

No further emission reduction scenarios are considered for first fill.

Vehicle Design

Workstream Description, Data Set Used, Refrigerant Emissions

This workstream assesses refrigerant emissions from passenger-vehicle air-conditioning (AC) systems in the European Union over the period **2021 to 2050**, with the objective of establishing a **robust quantitative baseline** and a consistent analytical framework to evaluate future proposed legislative measures.

The analysis focuses on **in-use refrigerant emissions**, that is, losses occurring during normal vehicle operation and servicing. These emissions arise primarily from permeation and leakage at hoses, elastomer seals, compressor interfaces, and service connections.

The baseline is explicitly defined to reflect **existing technology trends only**, including gradual improvements in AC system design and the increasing share of electric compressors associated with vehicle electrification. The emissions trajectory will serve as a neutral reference case against which the potential future emission reduction legislative measures that could realistically be implemented by **2030** can be applied and influence emissions through 2050.

¹ 2012 Report on Environmental Protection Efforts, Japan Automobile Manufacturers Association, inc., November 2012.
<https://www.jama.or.jp/english/>

Conceptual overview of refrigerant emission sources in vehicle AC systems (hoses, seals, compressors, service interfaces).

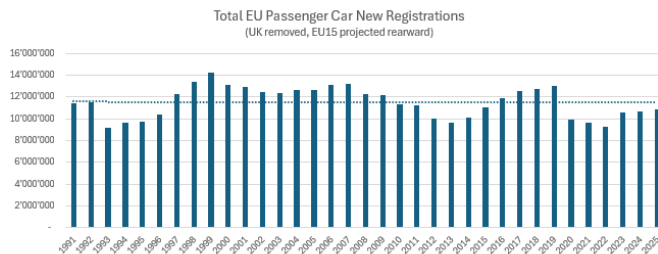
Emission source	Typical contribution
Hoses & permeation	Medium
Static seals	Low–Medium
Compressor shaft seal	High (ICE)
Service ports & connections	Medium
Other joints & fittings	Low

Description of Data Set Used

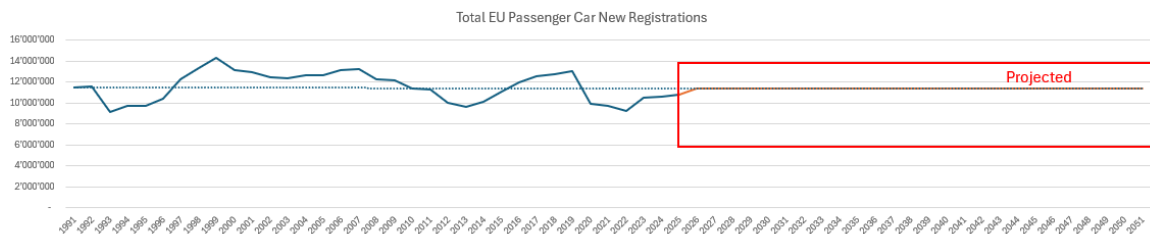
The analysis combines official fleet statistics with engineering-based leak-rate data and empirical OEM evidence.

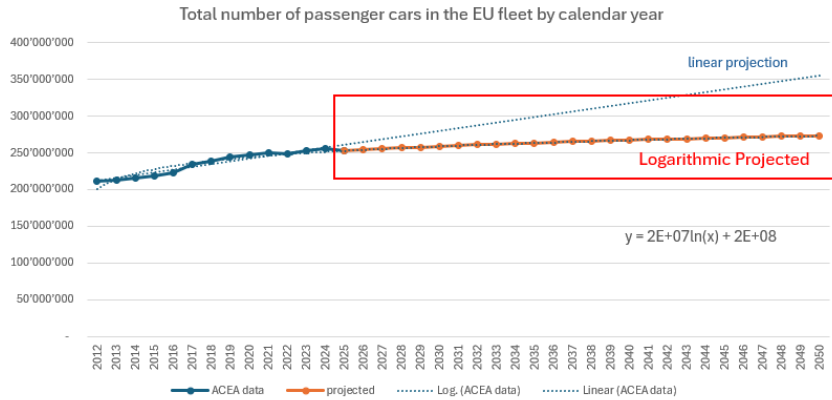
Data Set 1: Vehicle Population and Age Distributions

Vehicle population and age distributions are based on data published by the **European Automobile Manufacturers' Association (ACEA)**, including annual new vehicle registrations, total vehicles on the road, and reported average fleet age. Historical sales data by model year are used to construct a detailed age profile of the fleet extending back to the early 1990s. Where ACEA data are not available for future years, projections are applied that preserve consistency with observed fleet growth rates and reported average age.

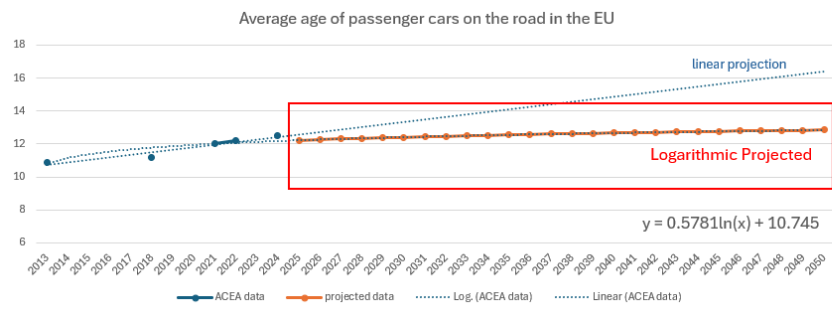


The model uses ACEA data on passenger new car registrations from 1991 through 2025. In earlier years, the UK data was subtracted and is not included in any point. All 27 countries are included. Some of the data from the expansion of the EU was not available and was projected in earlier years for inclusion. Although there will always be economic and other events that drive fluctuations in the market, the below chart uses a logarithmic projection that show new car registrations as flat at 11,400,000 average units a year. Where new car registrations are known (1991-2025), the actual data is used. In the future, the projected data is used. The plotted data is below.



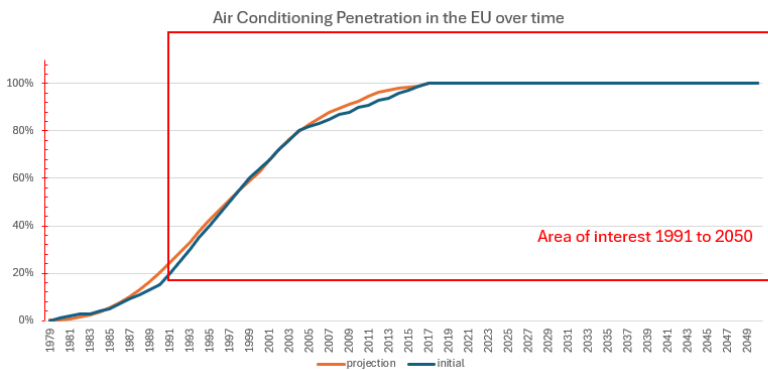


To model yearly refrigerant leak rates it is important to know the overall size of the EU fleet yearly. It is based on ACEA data with a Logarithmic Projection out to 2050. The linear projection would be disproportionate to expected population growth of the EU (17.4% vehicle growth over 10 years compared to 4% population growth over 10 years). The logarithmic projection mirrors the expected population growth at 4% over 10 years.



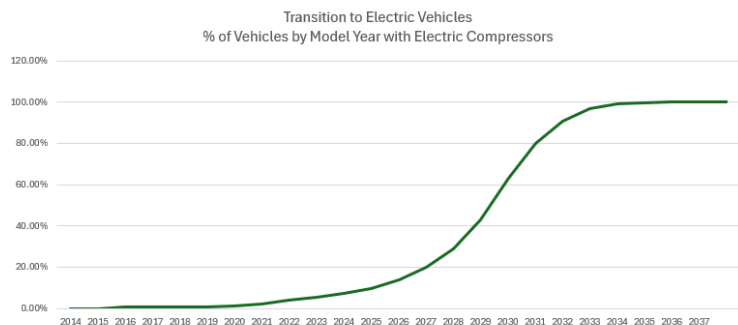
The average vehicle age is needed to project the distribution of vehicles in the fleet by age in a given year. The initial data is from ACEA and it is expected that the average vehicle age will increase. We used a logarithmic projection. The linear projection is also shown. It seems unlikely that the average vehicle age would soon exceed 15 or 16 years which would require a huge increase in vehicles 20 to 30 years old. Electric vehicles create a fair amount of uncertainty for long range projections. Mechanically, they are less complicated and could last longer, however current lithium ion battery technology suggests that life will be an issue.

Air-conditioning penetration is derived from historical OEM data points and industry reporting. In the early 1990s, AC was optional on a large share of EU passenger vehicles; penetration increased steadily through the 1990s and 2000s and approaches full penetration in new vehicle sales by the late 2010s. A smoothed curve fit is applied to estimate, for each model year, the proportion of vehicles originally equipped with AC. Under this approach, approximately **76% of vehicles on the road in 2021** were originally built with AC, rising to **about 97% by 2035** and effectively **100% by 2050** as older vehicles exit the fleet.



To estimate refrigerant leaks for the EU fleet, it's important to understand the number of vehicles, overtime that were originally built with AC. The data for this is only sparse. In 1979 few common vehicles in Europe were built with AC (higher end vehicles certainly were and exception). By 2017 the AC penetration was approaching 100%. We found additional references for points in-between. References are below. The orange data is shown as a smoothing curve to better estimate the points in-between. The data for both is below and the smoothed points were used in the calculations.

The model tries to anticipate the transition to electric vehicles and specifically to vehicles with an electric compressor. Both BEVs and strong hybrid vehicles will have electric compressors. Moving to electric compressors is important because it eliminates the compressor shaft lip seals which have a major effect on refrigerant leakage. Using SAE J2727 (a technology based leak rate tool) shows that leak rates can be improved by up to 6 g/yr depending on the compressor configurations used for evaluation. Compressor lip seals are also the only seal that is subject to wear (time, speed and temperature). Seals at joints (which do not move) are subject to temperature/time aging but are not subject to wear. Hoses do have some relative impact based on movement but they are more subject to time/temperature aging.



Data Set 2: Refrigerant Leak-Rate Parameters

Refrigerant leak-rate parameters draw on multiple sources. **SAE J2727** provides the reference framework for design-based mobile AC leak rates and reflects warranty-period system performance. This is complemented by manufacturer and field data, including measurements from OEM ICE vehicles, OEM BEV and (P)HEV platforms with electric compressors, and long-term in-use measurements required by the state of Minnesota². Together, these datasets provide:

- **Initial design leak rate** of the refrigerant due to the inherent design architecture (first 3 years)
- **Degeneration factor** (aging of the system) as seals wear out, fittings become loose due to vibrations, etc.

The base design leak rate data (actual and projected) are determined using the following assumptions:

- The 1991 design leak rate of 18g/yr is likely given single O-rings and non-barrier hose material
- Improved sealing technology over time and the increased use of electric compressors (no lip seal) account for reduced leak rates out to 2050 (see BEV/PHEV projection)
- The design leak rate (SAE J2727) is linearly projected and used to calculate aged leak rate which increase over time.

Design based leak rates represent the capability of a well-built vehicle based on the design configuration and technologies used for sealing. It is based on the SAE International standard J2727 for predicting refrigerant leaks. The standard is and has been a good way to move the industry to better overall designs, sealing technologies and manufacturing processes (like helium mass spectroscopy to check for leaks on components before assembly to the vehicle).

Much work has been done to validate the data including correlation to warranty on a wide vehicle basis, vehicle shed testing and mini shed testing (refrigeration system components only) and component testing. The standard is easy to use and understand (fewer possible leak joints and better sealing technologies that are less sensitive to assembly issues and improved manufacturing processes will reduce leaks overall).

The standard is used by every major vehicle manufacturer and the data is accepted and often required by many governmental regulators and agencies. It is accepted by EU type approval authorities, the US EPA, Canada and is required by the state of California (and was required by the state of Minnesota for vehicles with R-134a).

The upper line with dotted data points is a simple average of all data submitted to the state of Minnesota by year. It includes data from EU manufacturers, Japanese and Korean manufacturers and US manufacturers. It is not sales weighted and is indicative of the technologies in use at the time. It includes hundreds of vehicles and models over the years. The middle data with dotted points represents an average of OEM1 models over time for single evaporator ICE (Internal Combustion Engine) vehicles. The bottom dotted data again shows OEM1 data for (P)HEV (Plug in Hybrid Electric Vehicles) and BEV (battery Electric vehicles). OEM1 is considered a leader in refrigerant retention through improved sealing technologies. All of the above data comes from using the SAE International Standard J2727.

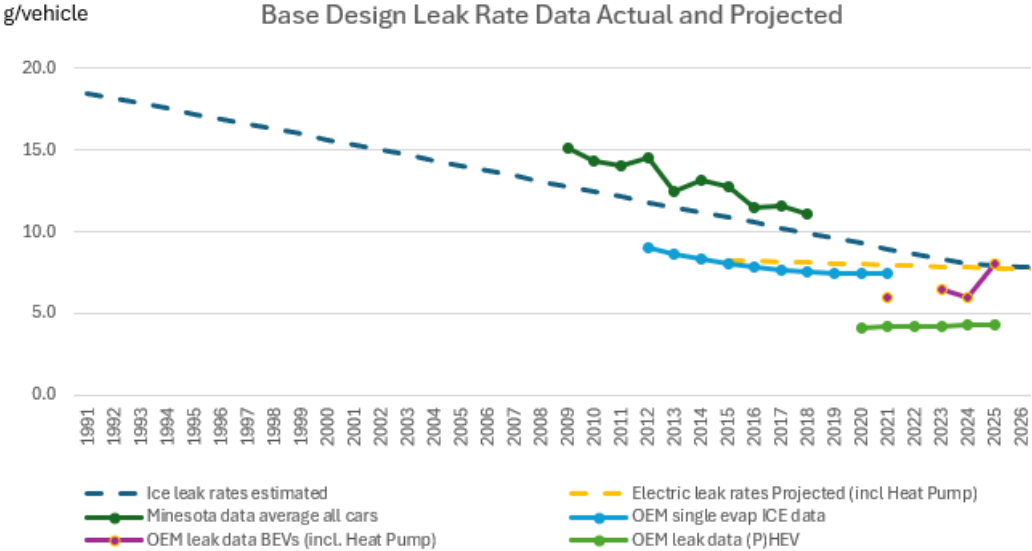
The dashed line projections represent the data used in this analysis. The upper dashed line represents a conservative estimate of overall industry leak rates (in g/yr) - better than the Minnesota

² <https://www.pca.state.mn.us/business-with-us/high-global-warming-potential-greenhouse-gases#:~:text=Leakage%20from%20vehicle%20air%20conditioners,t%20included%20in%20the%20requirement.>

data but not as good as OEM1 (an industry leader). For BEV vehicles this includes the introduction of the Heat Pump system (which usage of vapor injection and higher number of joints results) leads to higher emissions (~2g/yr). SAE J2727 was first published in 2005 based on work done in the early 2000's (it has been updated several times to include newer sealing technologies, new refrigerants, and electric compressors). The technologies used in 1991 are covered in 2005 (and later versions) and were very common at that time. The SAE document (explaining the worksheet) even shows examples of vehicles with leak rates of 18 and 20 g/yr. It is assumed the 18g/yr shown here is a conservative estimate. At that time, system durability was an issue, and companies were working to reduce warranty based on refrigerant leaks.

The upper dashed line has two parts (both linearly projected). The first part shows the natural transition of technology (between 1991 and 2024) to improve warranty and to meet regulations that were established both in the EU and the US (as well as other countries around the globe). The second part of this projection assumes that additional improvements will be made but at a different rate - one closer to the second dashed line shown for electric compressor vehicles (BEVs and many Hybrids). The leak rates used in this study projected out (to 2035 for ICE vehicles and 2050 for electric vehicles) are achievable today by OEM1.

The compressor shaft seal (on an ICE vehicle with a belt driven compressor) is by far the largest contributor to refrigerant leaks. Electric compressors do not have a shaft seal (an internal motor drives the compressor which is considered semi-hermetic). The leak reduction from switching to an electric compressor from a belt driven compressor can be between 2 to 3.5 g/yr with no other changes to the system. Vehicles with an electric compressor (all BEVs will have this) will automatically have lower leak rates - but may also have additional refrigerant connections for chillers and water-cooled condensers. If good sealing technologies are used (as in the case of OEM1) the effect of more seals is minimized.



Data set 3: Degeneration Factors and Maintenance

Most ICE vehicles without regular AC maintenance, no condenser cleaning, no AC health monitoring, etc. require an annual top-up at age 21-22

- Without preventative maintenance, no compulsory leak-checks, uncertain AC “health” condition
- ~25% charge size loss / year, ~125g/vehicle per year
- **Equates to degeneration factor of 14% / year for ICE (9% for BEV), starting after warranty period (year 4)**

Analysis Methodology and Assumptions Used

Predicting Fleet Size and Age

2021 Data and prediction			
In 2022 ACEA gives us actual data for:	ACEA Data	Projected	Correlation
Vehicles on the road by model year (2012 to 2021)	105'731'597		
total vehicles on the road in the EU older than 2021	143'239'152	144'581'564	100.94%
Total vehicles on the road in 2021	248'970'746	250'313'161	100.54%
The average age of passenger cars on EU roads	12.02	12.50	103.98%
We know the actual sales of vehicles by model year			
11th year starting point (percent of vehicles still on road)	93.9%		
Using an exponential projection for vehicles on the road	1.221		
percent of vehicles on the road 30 years old (should be <3.5%)		3.29%	
Average age of vehicles predicted vs ACEA (<.5 is acceptable)		acceptable	
<p>In 2022, ACEA gives us a breakdown of vehicles on the road from 2012 to 2021 by year. They also give us the total number of vehicles on the road older than 10 years (<2012) and the average age of passenger cars on the road across the EU in 2021. We are assuming the percentage of vehicles still on the road by model year is a relatively smooth deterioration curve when we look at the entire population of vehicles. We are also assuming that after 30 years more than 97% of the vehicles are no longer on the road (it will never be 100%). The percentage of vehicles on the road is multiplied by the actual sales for the year (and summed and divided by the total number of vehicles on the road) to determine the average age of vehicles on the road. We prioritize optimizing the number of vehicles on the road over the average age of vehicles. (vehicles are sold over the year so differences <.5 are acceptable)</p>			

Metric Tons of refrigerant release in 2021	
	11'654

The above number is highly influenced by the % of vehicles originally built with AC between 1991 and 2021 (**approx. 76%**)

2035 Data and prediction			
We can project some of the data for 2035	fleet size and age	Projected	Correlation
Total vehicles on the road in 2035 projected	263'561'077	256'322'867	97.25%
The average age of all vehicles on the road	12.56	12.50	99.54%
Number of years w/ nearly all vehicles on the road	9		
Low factor for deterioration in the number of years above 1st year starting point (percent of vehicles still on road)	1.2		
Higher deterioration factor for vehicles after above years	1.289		
percent of vehicles on the road 30 years old (should be <3.5%)		2.267%	
Average age of vehicles predicted vs ACEA (<.5 is acceptable)		acceptable	
<p>There is no available data from 2026 to 2035 and there is no data for the number of vehicles still in service in 2035 for 2025 to 2005. There is data on actual vehicle sales by model year for 2005 to 2025 which is used. Using the yearly vehicle sales projection, the total vehicles on the road projection and the average vehicle age projection we can model the distribution of vehicles on the road in 2035. By adjusting the figures in green we can approximate the fleet distribution. As above, we prioritize the total vehicles on the road and limit the average vehicle age to a half a year variation. We also limit the percentage of vehicles on the road at 30 years life to < 3%. The distribution is broken up into two sections (an initial section with fewer vehicles coming off the road and a second section where vehicles come off the road at a higher rate. The 2021 projection also had two sections - one with actual data and the second with a significant reduction of vehicles.</p>			

Metric Tons of refrigerant released in 2035	
	11'357

This number is highly influenced by the % of vehicles originally built with AC between 2005 and 2035 (**approx. 97%**)

2050 Data and prediction			
	fleet size and age	Projected	Correlation
Total vehicles on the road in 2050 projected	273'271'233	270'709'340	99.06%
The average age of all vehicles on the road	12.85	12.81	99.66%
Number of years w/ nearly all vehicles on the road	9		
Using an exponential projection for vehicles on the road	1.12		
1st year starting point (percent of vehicles still on road)	99.7%		
Higher deterioration factor for vehicles after above years	1.325		
percent of vehicles on the road 30 years old (should be <3.5%)		2.644%	
Average age of vehicles predicted vs ACEA (<0.5 is acceptable)		acceptable	
<p>There is no available data from 2026 to 2050 and there is no data for the number of vehicles still in service in 2050 for 2005 to 2025. There is data on actual vehicle sales by model year for 2020 to 2025 which is used. Using the yearly vehicle sales projection, the total vehicles on the road projection and the average vehicle age projection we can model the distribution of vehicles on the road in 2050. By adjusting the figures in green we can approximate the fleet distribution. As above, we limit the average vehicle age to a half a year variation. We also limit the percentage of vehicles on the road at 30 years life to < 3.5%. The distribution is broken up into two sections (an initial section with fewer vehicles coming off the road and a second section where vehicles come off the road at a higher rate. The 2021 projection also had two sections - one with actual data and the second with a significant reduction of vehicles.</p>			

Metric Tons of refrigerant released in 2050	
	8'851

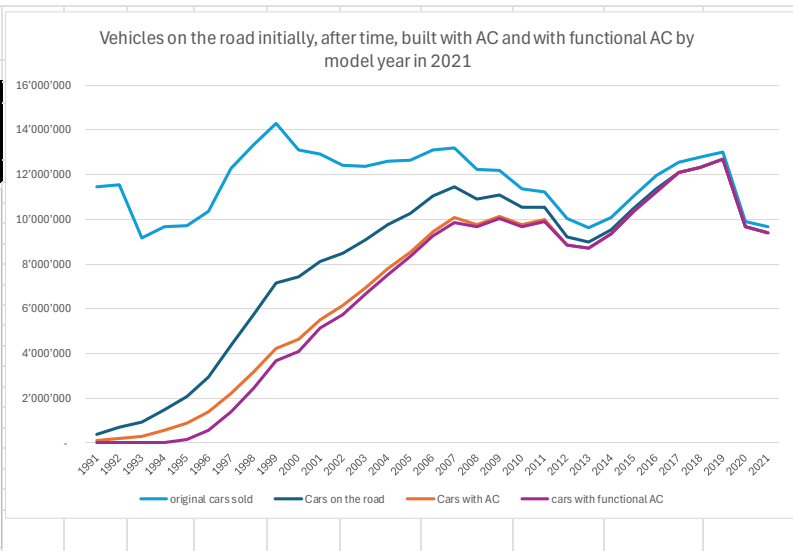
This number assumes 100 % of vehicles originally built with AC between 2005 and 2035 from tab on AC penetration

Predicting Cars with Working ACs

Predicting vehicles with functional AC in 2021	
	(>1 and <4)
Deterioration factor exponential	1.9
Number of service events after which 50% of the AC systems of vehicles (still on the road) are no longer being serviced	7.47
Vehicle age - years	24.00

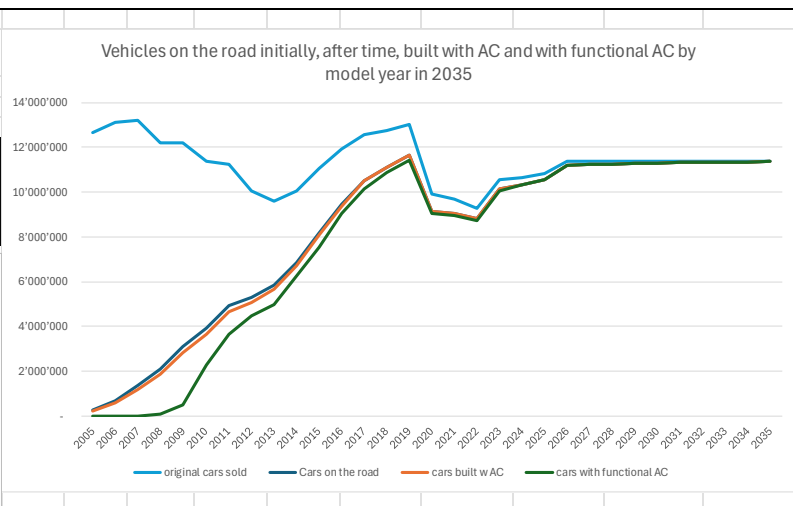
Not all vehicles "still on the road" that were built "with AC" still have a functional AC system. There is little data available on this but toward the "end of life" the cost of repair may not be justifiable to a consumers using the vehicle for simple transportation.

To approximate this we use a simple deterioration factor. In a further worksheet, we approximate when a vehicle would need to be serviced based on leak rates (by model year). Based on the deterioration factor selected we can see the average number of service events over the current life of the vehicle (in 2021) where 50% of the vehicles, still on the road would still have a functional AC system. We also show the age of the vehicle (where 50% are not functional) in years. This seems reasonable because vehicles not needing service yet or having been serviced only a few times in 10 to 15 years would have functional AC. Those that have required service many times (or approaching 30 years of life) are very unlikely to have functional AC systems. The calculated data, for the graph is to the right. The data below is used for the look up data in Blue above. The 2035 and 2050 graphs below.



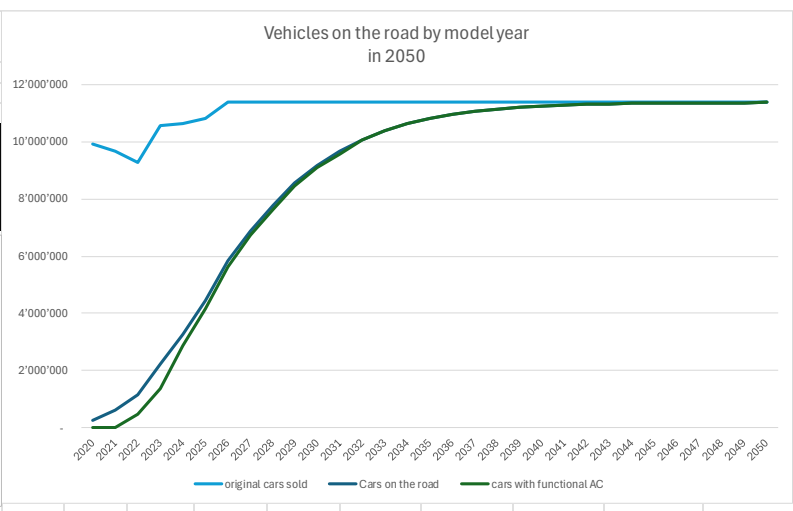
Predicting vehicles with functional AC in 2035	
	(>1.53 and <3.93)
Deterioration factor exponential	1.9
Number of service events after which 50% of the AC systems of vehicles (still on the road) are no longer being serviced	7.47
Vehicle age - years	25.00

Based on the deterioration factors selected (same as above) we can see the average number of service events over the current life of the vehicle (in 2035) where 50% of the vehicles, still on the road would still have a functional AC system. We also show the average age of vehicles (where 50% are not functional) in years. Because of lower leak rates in 2035 (which are biased by increased use of electric compressors) the average age to achieve 7.1 recharges increases to 25 years from 24 years above. The calculated data, for the graph is to the right. The data below is used for the look up data in Blue above. The 2050 graphs are below.



Predicting vehicles with functional AC in 2050	
	(>1.47 and <3.93)
Deterioration factor exponential	1.9
Number of service events after which 50% of the AC systems of vehicles (still on the road) are no longer being serviced	7.47
Vehicle age - years	27.00

By 2050, all vehicles on the road are expected to have been built with AC. Many of those vehicles will need a functional AC system to cool the batteries of a BEV. The ICE vehicles (2020 to 2035) may have vehicles that could operate without a functional AC system. We have used the same deterioration factor for the AC system and established where only 50% of the AC systems would be functional based on 7.1 estimated service events for low charge have occurred. In this case, That vehicle age moves out 2 years to 27 years based on the lower leak rates estimated in 2050.



Leak Deterioration

It is known that the initial design leak rates for vehicles from SAE J2727 are well accepted and were derived from 3-year warranty data. The leak rates derived in the standard are based on sealing technology used and not based on percent of charge which has no engineering basis. It is also known that a vehicle's leak rate deteriorates over time based on compressor lip seal wear, temperature exposure (causing seals and hoses to be more brittle) and general technology of the seals used (i.e., single O-rings vs seal washers). A deterioration factor of 14% was chosen (for ice vehicles) as a conservative estimate based on our calculation that a well-built vehicle (no assembly or component issues) in 1991 (18.5 g/yr initial leak rate) would, on average, go 8 years before needing it's first service. In addition, in the last years of life (>20 -30 yrs) for all vehicles (1991 to 2021) a vehicle with simple top offs (few component changes) would need the charge replenished each year or even more frequently. Both assumptions seemed conservative and reasonable when shared with industry experts. A deterioration factor of 9% was chosen for vehicles with an electric compressor (BEVs and strong hybrids) based on several factors: the elimination of the compressor lip seal (a major source of leaks in SAE J2727); generally reduced under hood temperatures (and temperature cycle extremes) with BEVs that help with hose and elastomeric seal aging; and a movement to better sealing technology because refrigerant leakage is now tied to battery safety and ultimately continued vehicle operation. The effect of extended usage based on heat pump operation in cold weather is unknown but elimination of the compressor lip seal - the only seal subject to wear by hours of operation - suggests this may be minimized. The internal temperature and high-pressure effect of heat pump operation in cold weather is also unknown, but it is assumed (because of battery safety and continued vehicle operation) that manufacturers have a high incentive to make improvements. For yearly leak rates, average charge level and average deterioration rates by year the value is adjusted, based on the proportion of ICE vehicles to vehicles with an electric compressor. For 1991 to 2014, there is no modification. Between 2015 until 2035, the numbers are adjusted proportionally and after 2035 it is assumed that all vehicles are BEVs.

Number of Recharges Without Repair (2021)

Total vehicles w/ functional AC in 2021	208'869'372	Percent needing service	18.4%	total service events 2021	38'446'764	Based on 120,000 service centers	Services per day	0.88	Estimated leak amount in 2021 w/ repairs	11'540
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This worksheet (and the others like it) are not used to calculate total leaks for the years 2021, 2035 and 2050 (although it used to verify the calculations are correct and consistent). The worksheet was intended to show each model year out for 30 years and calculate how often service would need to be performed (assumed only a top off was done). The worksheet uses leak data (assumes the first three years are the same) with deterioration to calculate when service would be required based on leaking a percentage of charge loss (variable in green to the right). Because not every vehicle will leak exactly the same, we apply a normal distribution with one Sigma equal to one year (shown to the right) at the point that the cumulative leak rate shows that service is required. At the time of service we assume the charge will be reset to the correct amount. As an example, the 2012 model year would need to be recharged in it's 11th year on average (R60). Some of that service would happen in the 10th year based on the normal distribution and shown in 2021 in the box (Q62). The percentage is shown in the box and is multiplied by the number of vehicles on the road in 2021 (B60). The boxed numbers (representing service events in 2021) when multiplied by the number of vehicles on the road, originally built with AC, and with functional AC systems. When service events become closer (toward the end of life), the distributions overlap and are added to get the boxed number (examples of this are shown far below (AB172 to AM294). Adding these up gives you the number of service events expected in 2021 and shown above (F3). With roughly 120,000 vehicle service shops in the EU - that represents less than 1 event per day as shown above (H3).

Model Year	Number of vehicles built with AC still functional in 2021	Yrs to first service for a well built vehicle	Recharges expected with ave 20.5 year life	Recharges possible with a 30 year life	Base charge	recharge @	30%
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A service event that is predicted in year 6 is actually spread out over years 4 through 9. If service events are close, the distributions overlap and increase accordingly.

Number of Recharges With Repair (2021)

Total vehicles w/ functional AC in 2021	208'869'372	Percent needing service	13.1%	total service events 2021	27'348'966	Based on 120,000 service centers	Services per day	0.62	Estimated leak amount in 2021 w/	7'381						
<p>This worksheet was intended to capture the effect of using service equipment that requires the vehicle to pass a vacuum leak check before a vehicle charge can be done. The worksheet uses the same calculations as the previous worksheet with the exception that when the deteriorated leak rate reaches a 40g/yr level (variable - confirmed as plausibly by one of the major equipment manufacturers and used in all US equipment for R-1234yf today), some service would have to be done to improve the leak rate. Generally, a technician would look as to where a significant leak exists (using fluorescent dye or using a hand held leak detector). A seal, hose or part would need to be replaced. Because we are not replacing every part, the vehicle does not go back to its original leak rate. In this case we assumed that the deteriorated leak rate would improve by 25% (variable). An example (there are many) of this can be found below on a 2007 vehicle (V80 to W80) in its 16th year. The result of this would be fewer total leaks in 2021 and fewer repair events in the same year because repairs would be required. This is rhetorical for 2021 because we can't change events in the past. We can change events that happen in the future so the 2035 and 2050 estimations are well within reach assuming 10 years would give an opportunity to move to improved equipment that is in use in the US today.</p>						<table border="1"> <tr> <td>recharge @</td> <td>Leak rate requiring service g/yr</td> <td>ave leak reduction after service</td> </tr> <tr> <td>30%</td> <td>40.00</td> <td>25%</td> </tr> </table>		recharge @	Leak rate requiring service g/yr	ave leak reduction after service	30%	40.00	25%			
recharge @	Leak rate requiring service g/yr	ave leak reduction after service														
30%	40.00	25%														
Model Year	Number of vehicles built with AC still functional in 2021	Yrs to first service for a well built vehicle	Recharges expected with ave 20.5 year life	Recharges possible with 30 year life	Base charge	<p>A service event that is predicted in year 6 is actually spread out over years 4 through 9. if service events are close, the distributions overlap and increase accordingly.</p>										

Legislative Measures Considered

Potential Legislative Measures By 2030, Description, Feasibility, Affordability

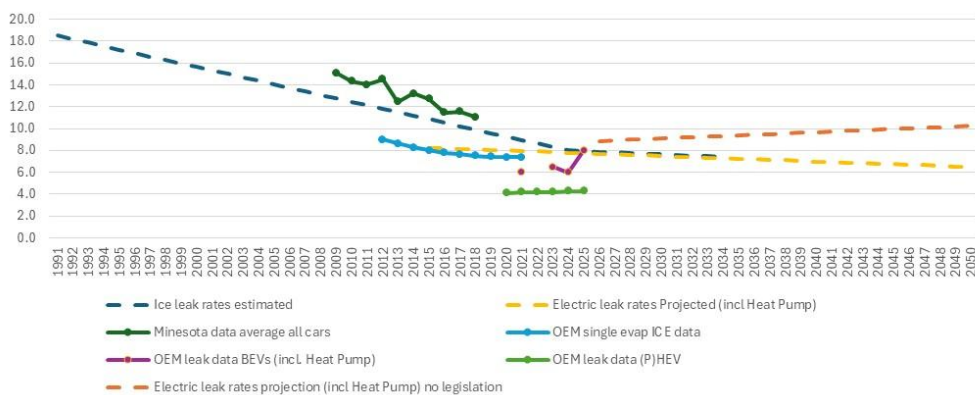
OEMs make different design choices that impact refrigerant emissions

- Different design architectures show a difference in refrigerant emission rates e.g. (P)HEV versus BEV versus ICE
- Different OEMs make different investment choices (reducing refrigerant emissions has a cost impact) e.g. OEM ICE data shows lower refrigerant g/vehicle emissions compared to industry ICE Minnesota data

Measure 1: Maximum Design Leak Rates

- Set maximum design leak rates for new vehicle type certification to allow the whole industry to invest in lower initial design refrigerant leak rates
- Cost pressure and lack of legislation could reverse the trend of lower refrigerant design leak rates (e.g. back Minnesota state³ levels 8.5g/r for BEV without Heat Pump hence resulting in 10.25g/yr with Heat Pump)
- Set targets such that the industry can catch up to best in class today by 2050

Base Design Leak Rate Data Actual and Projected



³ <https://www.pca.state.mn.us/business-with-us/high-global-warming-potential-greenhouse-gases#:~:text=Leakage%20from%20vehicle%20air%20conditioners,t%20included%20in%20the%20requirement.>

Measure 2: Mandatory Repair of the AC System in Case a Leak is Detected During Service (service machine vacuum test)

This means that underlying leaks are systematically eliminated during service (assumed not common practice today).

- The mandatory repair assumption **reduces the total accumulative leak rate once after repair by 25%** (in case the leak rate/year is >40g/year) and continued progression at the same degeneration factor afterwards
- This is tackling the practice of continuous top-up without investigating whether a leak exists that requires repair. This would mandate repair, not just top up, triggered by the machine vacuum test pass rate (40g/year leak maximum leak rate allowed)

Measure 3: Ensure the AC system is running in optimal conditions (AC check, no visual leaks, troubleshooting in case of low refrigerant level); **increase component life due to optimal AC running conditions for a well-maintained system due to less wear and tear (30-50%)**

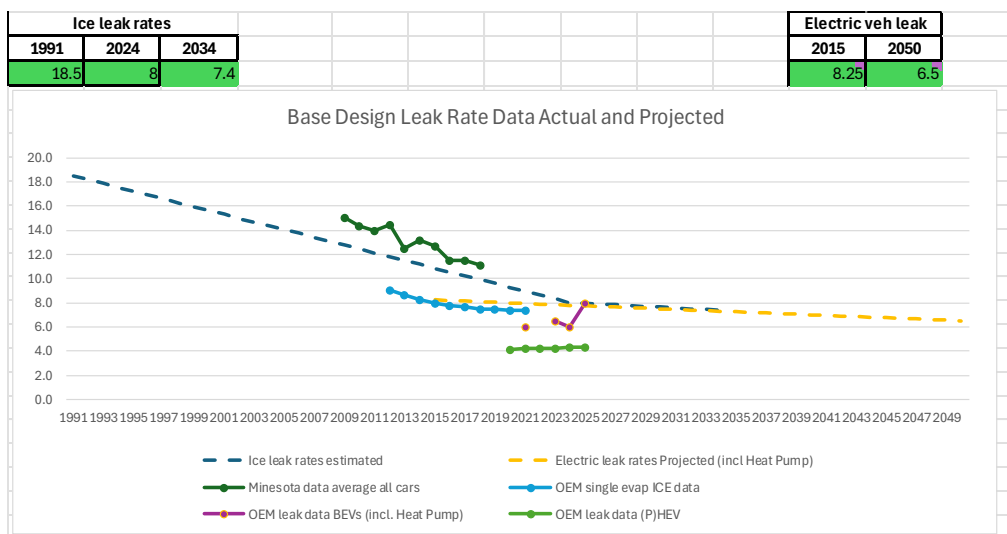
- Compulsory AC check / inspection / condenser washing / check for debris during major service and inspection road worthiness testing (refer to Measure 1 in the repair section)
- Increased condenser design robustness, Compulsory AC health monitoring, tethered service port caps
- Reduction of the **degeneration factor for ICE from 14% to 11% and BEV from 9% to 7% post 2030**

This is conservative, as:

- AC health monitoring already in use for many BEVs and often part of integrated thermal management system (not all) and some ICE/PHEVs
- some OEMs already use internal specification close to the proposed condenser spec for newer vehicles (<10 yrs old) but not all OEMs.

Scenario	Leak rate assumptions						
	BEV-PHEV design leak rate g/vehicle		Deterioration factor ICE / EV-PHEV				
	2015	2050	2029	2035	2040	2045	2050
Status quo, lowest cost as no regulatory requirements	8.25	10.25	14% / 9%	14% / 9%	14% / 9%	14% / 9%	14% / 9%
Max leak rate legislation implementation, 14%/9% degeneration	8.25	6.5	14% / 9%	14% / 9%	14% / 9%	14% / 9%	14% / 9%
Max leak rate legislation implementation, 11%/7% degeneration with repair obligat	8.25	6.5	14% / 9%	11% / 7%	11% / 7%	11% / 7%	11% / 7%

This would entail the following maximum leak rate definition (resulting in 6.5g/vehicle incl. Heat Pump by 2050):



Emission Reduction Scenarios (2030–2050)

Emission Reduction Scenarios Based on Potential Legislative Measures by 2030

The emission reduction scenarios are based on a reduction of:

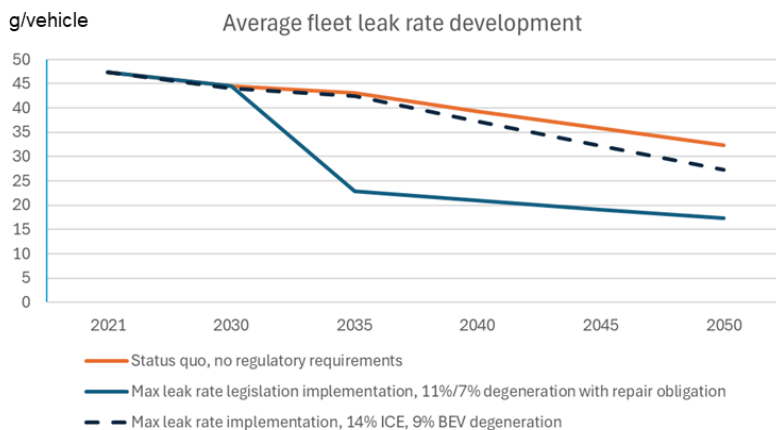
- **Initial design leak rate** of the refrigerant due to the inherent design architecture (first 3 years)
- **Degeneration factor** (aging of the system) as seals wear out, fittings become loose due to vibrations, etc. An obligation to repair would reduce the degeneration factor.

Emissions from service and component failure are captured in the designated workstream.

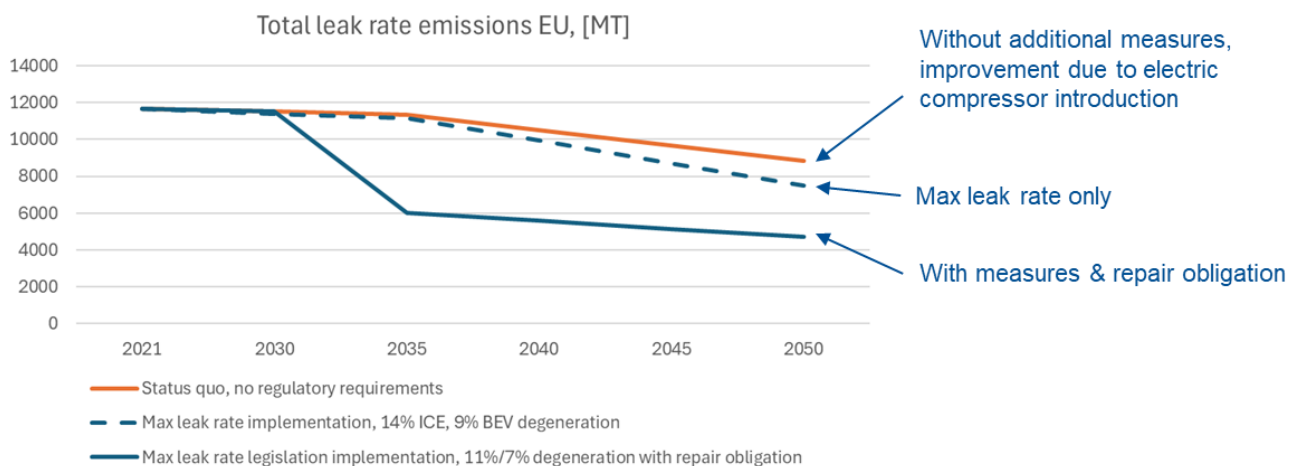
Modelling assumption post 2030: degeneration rate reduction from 14% to 11% for ICE and from 9% to 7% for BEV-PHEV.

- Assuming all vehicles are **well maintained** (obligation from 2030 onwards)
- Introduction (21 years) of additional measures:
 - Compulsory inspection / condenser washing / check for debris during major service & inspection road worthiness
 - Increased condenser design robustness, Compulsory AC health monitoring, tethered service port caps
- >15 years of ~100% electric compressor usage during new build

Overall degeneration leak rate reduction from ~45g/vehicle in 2021 to ~<20g/vehicle by 2050⁴



2030-2050 overall refrigerant emission reduction versus “without measures” ~40-45%⁴



⁴ Using the design architecture emission model, calculations for 2021, 2035 and 2050 where 2030, 2040 and 2045 are determined via linear interpolation.

Vehicle Accidents

Workstream description, data set used, refrigerant emissions

The accidents workstream covers all accident-related (e.g. collision) refrigerant emissions. It is assumed the full charge size is emitted in case of an accident.

Description of Data Set Used

Data set 1: Driving aids – legislation in EU & implementation timelines

The EU has implemented several measures in GSR 2019/2144 to improve driver safety⁵:

- **Autonomous Emergency Braking (AEB):** Detects potential forward collisions with vehicles, pedestrians, and cyclists, issuing warnings and automatically braking if the driver doesn't respond.
- **Intelligent Speed Assistance (ISA):** Helps drivers adhere to speed limits by controlling vehicle speed, with driver overriding available.
- **Driver Drowsiness and Attention Warning (DDAW):** Monitors driver attention and warns of fatigue or distraction.
- **Emergency Lane Keeping Systems (ELKS):** Assists in preventing unintentional lane departures.
- **Reversing Detection Systems (REV):** Warns of obstacles behind the vehicle, crucial for safety.
- **Implementation Timeline (GSR 2019/2144):**
 - **July 2022: New type approvals (M1/N1 vehicles) must have AEB (car-to-car) and DDAW.**
 - July 2024: AEB for pedestrians/cyclist's mandatory for new types; **ELKS & DDAW** for buses/trucks.
 - July 2026: AEB (pedestrian/cyclist) mandatory for all new commercial vehicles; ISA for all new vehicles.

Modelling assumptions: implementation following legislation requirements

Data set 2: Effectiveness of driving aids

The effectiveness of driving aides (Advanced Driver-Assistance Systems, ADAS) has been studied by the Association of Insurance Companies⁶ and the SWOV⁷ in the Netherlands. The Netherlands has an average car age close of 11.9 years which is close to the European average of 11.8 years⁸, as well as a relatively complex road network, hence a good representation. A total of 692,951 private passenger cars were included in the dataset⁶, of which 14.9% were involved in at least one accident between 2015 and 2022. Within this group of accidents, 1.5% occurred in poor weather conditions on 81 days with code red and code orange warnings in the Netherlands.

The data set shows a significant reduction in the risk of an accident. This can be divided into two Groups:

- 1) Systems related to **AEB**: Collision detection and Autonomous Emergency Braking
- 2) Systems related to **ELKS**: Lane detection and Lane keeping

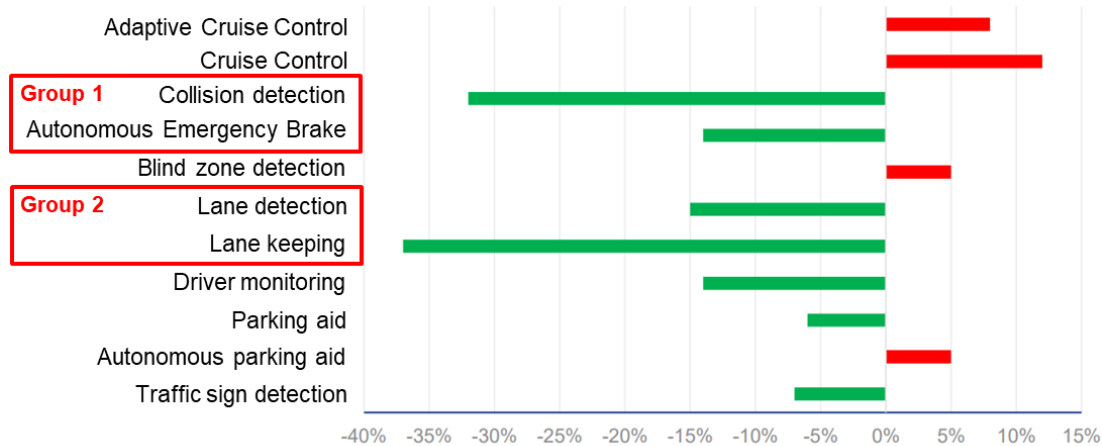
⁵ <https://eur-lex.europa.eu/eli/reg/2019/2144/oj/eng>

⁶ https://www.verzekeraars.nl/media/xepdraxc/samenvatting-onderzoek_geavanceerde-rijhulpsystemen-adas-verkeersveiligheid-en-co2-uitstoot_02-2024_nederlands.pdf

⁷ <https://swov.nl/sites/default/files/bestanden/downloads/R-2024-16.pdf>

⁸ <https://aut.fi/en/statistics/international-statistics/average-age-of-passenger-cars-in-european-countries/>

Effect of ADAS (%) on Risk of Accident



Analysis Methodology and Assumptions Used

The Target Crash Population For Crash Avoidance Technologies in Passenger Vehicles have been well described by, Wang, 2019, NHTSA⁹:

- Hereby it is assumed: Group 1 & 2 would in most cases lead to severe traffic accident leading to a full charge release.
- Group 1, forward collision, reported front-to-rear (or rear-end) crashes represented 29.4 percent of all reported crashes
- Group 2, lane keeping, lane departure (type) crashes represented 19.4 percent of all reported crashes

The impact of the driving aids in Group 1 and 2 can be added sequentially. Hence the reduction of the number of accidents due to Group 1 and 2 combined can be calculated by basing Group 2 reduction on the reduced amount of accidents related to Group 1.⁷

The amount of Road traffic accidents (2009-2019 and 2013-2023) have been reported by the Statistic of Road Traffic Accidents, UNECE, in Europe and North America, United Nations, 2021¹⁰ and 2026¹¹ (some interpolation was required where interim years were not reported). This has been used to determine the total amount of road accidents.

The technology introduction is following the introduction of EU legislation. This is following GSR 2019/2144⁵:

- Group 1: 2022
- Group 2: 2024

⁹https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjst7vloO6TAxWGH_0HHXj1D04QFnoECBoQAQ&url=https%3A%2F%2Fcrashstats.nhtsa.dot.gov%2FApi%2FPublic%2FPublication%2F812653&usg=AOvVaw1CWuAloe3qVzrFuhKvifxl&opi=89978449

¹⁰ https://unece.org/sites/default/files/2022-01/2113621_E_pdf_web.pdf

¹¹ https://unece.org/sites/default/files/2026-02/2518859_E_PDF_WEB.pdf

Legislative Measures by 2030

Potential Legislative Measures by 2030, Description, Feasibility, Affordability

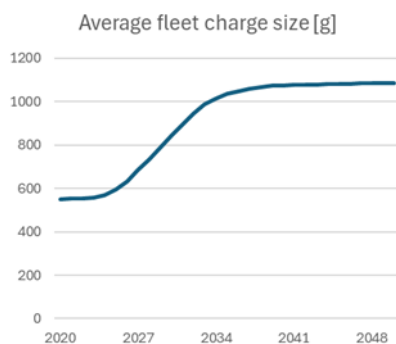
The inclusion of driver aids to improve driver safety (reducing the amount of injuries and fatalities involved in road accidents) is included in legislation introduced in 2019. This requires AEB in 2022 and ELKS in 2024. These driver aid systems have been introduced by OEMs already well in advance of the required introduction via legislation. It is therefore a conservative assumption that fleet introduction has only started in 2022 and 2024. In addition, it is expected that future autonomous vehicle technologies will be able to further reduce accidents, but this has not been taken into account (to remain conservative). Therefore, there is only one scenario modelled, the baseline scenario.

Emission Reduction Scenarios (2030–2050)

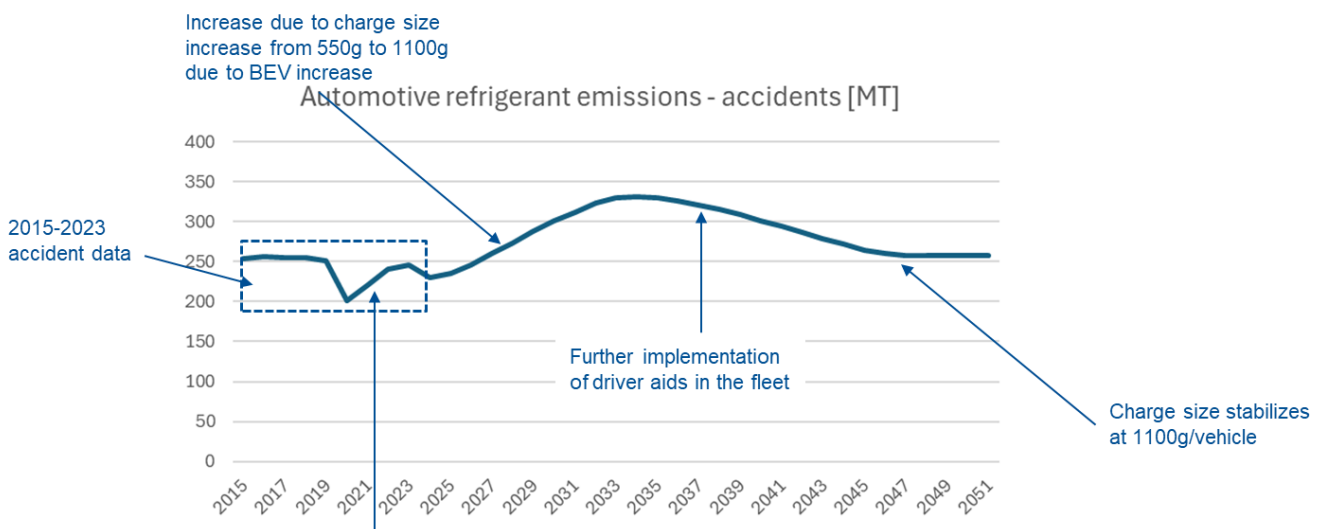
Emission Reduction Scenarios Based on Potential Legislative Measures by 2030

There is no other scenario than the baseline refrigerant emission modelling as legislation is already in force today to introduce driver aids.

It is noteworthy that the average charge size will increase significantly between 2025 and 2035 from 550g/vehicle to 1100g/vehicle.



For the time period 2030-2050, the overall refrigerant emission reduction (driver aids) is compensating the increase in charge size.



Repairs

Workstream Description, Data Set Used, Refrigerant Emissions

The repairs workstream covers all non-accident related work on the AC system where the user of the vehicle has noticed a performance issue with the AC system. A typical complaint can be:

- Warm or Mild Air Blowing
- Weak or Reduced Airflow
- Strange Noises When AC is On
 - Grinding/Squealing: Often indicates a failing compressor or a worn-out belt.
 - Rattling/Knocking: Possible loose components or debris in the blower fan.
 - Clicking: Compressor clutch is attempting to engage but failing.
- Musty or Foul Odors
- Water Leaking Inside the Cabin
- AC Intermittently Working
- When to Seek Immediate Service
 - Burning Smell: Can indicate an overheating blower motor or electrical wiring issues.
 - Sweet/Chemical Smell: Often indicates a refrigerant leak (refrigerant can have a slightly sweet odour).
 - Engine Overheating: If the AC failure is accompanied by a "check engine" light or the engine temperature rising, it indicates a serious problem requiring immediate attention.

The workstream includes repair, where a failure is detected that is component related:

- The user has issue, a component failure
- In many cases, the full charge is lost (40/70 = 57%)
- Aim is to reduce the risk of a full charge loss by
 - Increasing detection of a leak early (before the leak deteriorates and the leak rate increases)
 - Increasing product robustness to failure (e.g. increase corrosion resistance, increase resistance against stone impact)

This workstream does not include:

- Any refrigerant top up volumes (part of vehicle design workstream) or continued higher refrigerant emissions as repairs are not carried out (but instead, only a top up is carried out without actually addressing the real issue).
- Any refrigerant loss due to accidents

Description of Data Set Used

Data set 1: Garage: non-accident-related service data (average vehicle age 11.3)

Data set: 250k services (across France) carried out in 2024, charge size ~550g.

France is a good representative market for the EU as it offers a good mix of coastal areas (important to represent corrosion resistance) as well as rural areas (with unpaved roads increasing the risk of stone damage). Much of Europe (including France¹²) that commonly salts (northwestern Europe, Germany, Scandinavia) has frequent freeze–thaw cycles and coastal moderation where NaCl remains

¹² <https://www.eurosalt.nl/en/salt-in-france/>

effective and economical. Also, Western Europe (e.g., Germany/Netherlands) has dense networks, shorter distances to depots, and milder winters in many areas make widespread NaCl anti-icing spraying more common and visible.

This data showed for these 250k services:

- 70%, AC does not work
 - o 50% (% points of the 70%) Leak detected that needs repair
 - o 20% (% points of the 70%) AC break down, component failure, requires work, compressor change, other component change
- 30% preventative maintenance, just requires top up, leak check is passed

In case of leaks or AC break down:

- 70% condenser issue
- 13% compressor issue
- 17% hoses, other issues

For 40% leak or break down cases, no refrigerant left, it is assumed that:

- ~80% related to condenser issue
- ~20% related to other issues

Total services 250k	Work required	Refrigerant loss, EU [MT], 2024
30%	Top-up, no leak	366 ¹³
70%	Condenser failure (70%)	1469
	Compressor issue (13%)	256
	Hoses, other issues (17%)	290
	Sub total	2016
Grand total		2382
Refrigerant consumption	R-134a + R-1234yf actuals	2380

The above table shows the refrigerant consumption for the EU based on the 250k services (scaled by the vehicle population in France). The average service without full charge loss (calculated based on # services with full charge loss as part of total and actual refrigerant consumption) is 125g (on 550g charge size, 22.75% of total, hence close to 25%).

From the above table it can be calculated that condenser failure equates to ~63% of total service emissions.

Data set 1 provided further insights, in case of:

- **AC Issues:** In 70% of cases involving AC problems, the cause is a leak in the condenser or its circuit (pipes, connections, etc.). These vehicles are typically found to be mostly empty of charge.

¹³ For reference only, top-up volumes considered as part of design architecture.

- **Condenser Issues:** Micro-leaks¹⁴ caused by gravel or road debris are the most common issue.
- **Breakdown Mapping:** Vehicle design and type are more significant factors than age. Some newer R1234yf vehicles are more exposed due to lower circuit capacities (approximately 100g less).
- **Service caps missing:** Estimated to happen for <20% of the vehicles entering service. During servicing, technicians often place them on the windshield cowl or near the engine compartment, and they can occasionally be forgotten or fall into hard-to-reach areas.

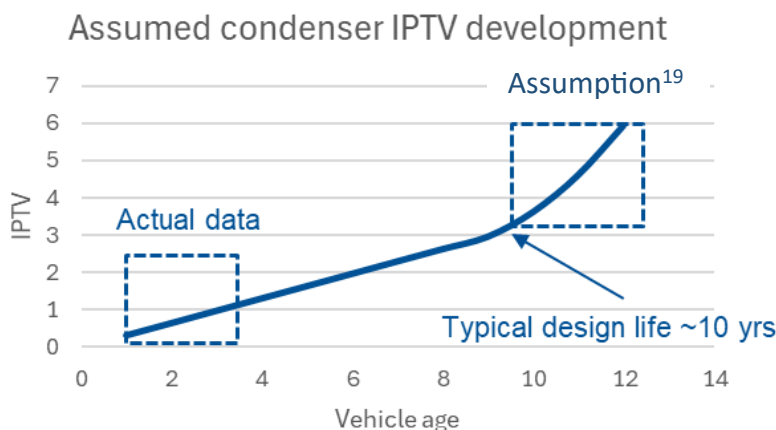
Following data regarding average vehicle age for servicing:

- R-134a vehicles: 14.4 years, 56% of services¹⁵
- R-1234yf vehicles: 7.3 years, 44% of services¹⁶
- IPTV (Incidents Per Thousand Vehicles): 18.4 (at average of 11.3 years)¹⁷

Data set 2: Tier 1 Warranty: non-accident-related service data

Based on Tier 1 warranty data, it is concluded that:

- IPTV (Incidents Per Thousand Vehicles) condenser:
 - Year 1: 0.3 Total
 - Year 3: 1.0 Total
 - Year 3: ~0.1 Identified as “damage” to condenser; can include stone damage (NA)
- IPTV other components are lower
- IPTV warranty condenser includes (~typical):
 - Overall corrosion protection
 - Increased leading edge thickness¹⁸
- Different condenser design specifications per OEM (can vary significantly)
- **IPTV at year 11.3 ~5.0** (assuming non-linear increase beyond 10 years of age¹⁹)



¹⁴ Cause of micro-leak may be difficult to assess (e.g. corrosion vs debris)

¹⁵ Aligns to the estimated R-1234yf / R-134a market ratio based on EU average

¹⁶ *Ibid.*;

¹⁷ 250k services (out of 6.66M vehicles) in total of which 70% have AC problems of which 70% have condenser issues = (250,000 x 0.7 x 0.7) / 6660

¹⁸ For certain Tier 1 designs, folded tube and center condensers, went to double thickness nose starting around 2012 which served as higher protection against stone damage.

¹⁹ no data/information regarding failure leak rate or damage at 10-15 years

Other observations:

- **Corrosion will certainly play a significant role** particularly in certain environments, for instance high road salt use areas, by the oceans, etc. (typically the case for Western Europe with **frequent freeze-thaw cycles** during the winter)
- Study concluded that stone damage to condensers was generally to **specific vehicles and a redesign of cooling module**. Added stone guards, is advised more so than condenser change.
- Use of a radiator in front of the condenser such as a Low Temperature Radiator in EVs will result in some stone damage to this component and less to the Condenser

Legislative Measures Considered

Potential Legislative Measures by 2030, Description, Feasibility, Affordability

Measure 1²⁰: Increased AC System Check & Leak Inspection

- **Include UV dye (SAE J2297 standard)**, very low cost, <1 €/vehicle:
 - First fill, OEM level (many already do like e.g. all NA OEMs, etc.)
 - Existing vehicles (without UV dye), if AC parts are replaced e.g. desiccant (that includes UV dye)
 - During RRR-machine vehicle service, introduce UV dye during the final charging phase of the service
- **AC Check and Requirement to clean condenser** (simple low pressure water spray, carefully applied not to damage the condenser fins) and **check for blockage and UV dye evidence of leaks** (requirement to repair) at major car service like oil / break fluid change would help significantly against corrosion damage or overheating and doesn't cost much (only takes a few minutes if the condenser is accessible).
- **Road worthiness testing, visual check for UV dye evidence for leaks** (requirement to repair to pass the test, garage certification AC inspection has been carried out)

Measure 2: Condenser Design Robustness Specification

- Corrosion resistance and stone damage are major drivers for the condenser issues/repairs (IPTV 18.4). OEM warranty data shows (IPTV = 0.3, 1 year, IPTV = 1.0, 3 years, IPTV stone impingement = 0.1, 1 year). An industry condenser design specification does not exist, hence corrosion resistance and robustness against stone damage varies significantly.
- **This requires a condenser “SAE industry style” standard** (e.g. similar to SAE J2842) to push overall design >10 years that defines:
 - Define aspects covering corrosion resistance:
 - Brazing quality assurance requirements
 - Zinc arc spray surface treatment
 - Careful design of the seal around the condenser that prevents the air from going around the condenser. Material selection here around the condenser is key to minimize the corrosion risk of the condenser²¹.
 - Define aspects covering robustness against damage:
 - **Double nose design (maximum practical thickness)** at the leading edge (stone guards may be considered in addition)

²⁰ Inspection / condenser cleaning where components are easily accessible. Where components are not accessible without extensive part removal, relying on AC Health monitoring is compulsory

²¹ The seal material and design along the bottom and sides of the condenser should be designed as best possible not to trap debris causing extended wetness and accelerating corrosion

Measure 3: AC Health Monitoring, Requires Development of a “SAE Standard” to Functionally Define:

- The HVAC system should continuously measure:
 - Ambient temperature;
 - Evaporator inlet temperature;
 - Cabin outlet temperature (interior cabin temperature);
 - Battery coolant temperature (if applicable);
 - Refrigerant pressure transducer;
 - The status of the A/C and/or heater ON/OFF switch on the cabin control panel;
 - The temperature selected by the rotary dial on the driver’s control panel.
- And monitor for unusual behavior (that would trigger a service notification):
 - Indication of condenser blockage, filter blockage
 - Refrigerant pressure (versus table with expected pressure at certain ambient temperature at start)
 - Compressor power draw to achieve requested cabin temperature
 - Ability to achieve the requested cabin temperature

The overall goal of the AC Health monitoring is to set a criteria for servicing to increase AC equipment life expectancy and reduce risk of major event leading to a full refrigerant charge release (requires software²² / tables & calibration to be developed per OEM).

Measure 4: Obligation to Use Tethered Closure Caps

- Field experience has shown that AC closure caps are not always fitted after a service is completed (the cap may get lost, forgotten, could fall into the engine bay), this could represent up to 20% of the vehicles entering for a service
- The cap is an integral part of the port²³:
 - Security of this cap is essential to the leak integrity of the port²⁴
 - These caps include a rubber seal around the port mouth (primary seal, otherwise a small amount of refrigerant will leak over time)
 - SAE J639 requires caps be used for charge ports and suggest that these caps be tethered to prevent loss
 - Mandate use of tethered closure caps (experience shows significant lower risk of missing cap if tethered)
 - Used during first fill
 - Retrofit any vehicle coming in for visual AC inspection or AC service
- SAE-J3267, January 2022, Automotive Air-Conditioning Service Ports Task Force Field Survey Results. Main conclusion: Missing service port caps are common; allowing debris and corrosion to impact the sealing and integrity of the port. The older the vehicle, the more likely it is to be missing service port caps.
- Visually check if AC port cap is fitted during roadworthiness testing
- Total emissions: 20% of 250M vehicles, 5g/year²⁵ leak due to missing caps = 250MT/yr
- A tethered cap is very low in cost (< 1€/vehicle²⁶) and takes little time to fit

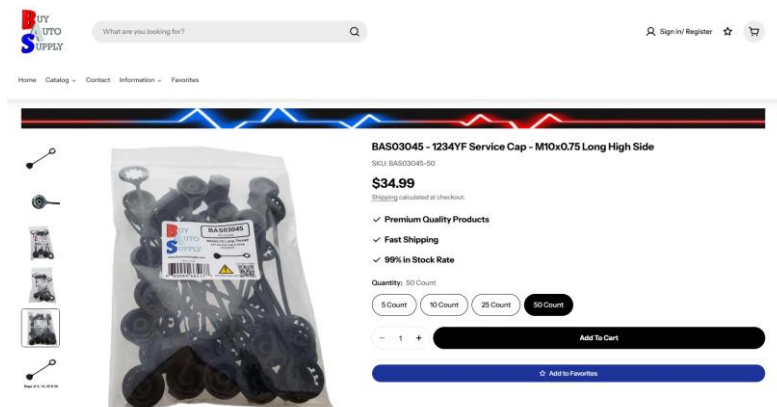
²² E.g. Predictive Repair of Vehicle R1234yf Refrigerant Systems Based on Monitoring of Micro-Leakages: Department of Vehicle Maintenance and Diagnostics, AHFE, Szechenyi Istvan University, H-9025 Gyor, Hungary, <https://www.mdpi.com/2075-1702/14/3/268>

²³ <https://schrader-pacific.com/wp-content/uploads/AC-Valve-Manual.pdf>

²⁴ On a trial with 8 vehicles, 13 out of 16 caps showed detectable refrigerant leaking when caps were removed and the engine was running. These leaks all disappeared once caps were appropriately fitted. <https://www.autoacforum.com/viewtopic.php?t=15043>

²⁵ Typical refrigerant sensitivity detection level of a sniffer is ~5g/year equivalent leak (hand- held device, medium sensitivity). <https://climalife.com/leak-detection-for-refrigeration-systems-a-major-challenge-for-the-21st-century/>

²⁶ <https://www.buyautosupply.com/products/bas03045-1234yf-service-cap-m10x0-75-long-high-side?variant=43328017170525>



Example of a tethered service port cap²⁷

Analysis Methodology and Assumptions Used

Measure 1²⁸: AC Check & Visual Inspection, AC Cleaning with Water / Debris Clearing During Each Regular Major Service incl. UV Dye (requirement to repair)

- Average charge loss can be limited to 125g max or ~25% of charge (of cases identified in 2024 as full charge loss)
- Full charge losses will still happen, but are more aligned with warranty data (e.g. 0.1 IPTV relating to stone damage results in 26k incidents in EU/year resulting in <15MT emissions)
- An AC check & visual inspection and cleaning certificate should be issued with each major service as proof during road worthiness testing that the AC system has been checked in the last 2 years.
 - Lifetime cost impact: ~200 €/vehicle during lifetime
 - Typical visual inspection and cleaning lasts ~10-15 mins. Average end of life age for a vehicle is 19-20 years old (see end of life section), hence a vehicle will require 8-10 additional inspections (~2 hrs of inspection).
 - Based on average mechanic dealership hourly rates²⁹ (France as average proxy in EU, between 50€ to 120€/hr, hence ~85€/hr) the approximate lifetime costs are ~200€

Measure 2: Inspections, Including Road Worthiness, Requirement To Repair To Pass The Test

- Overall **early detection of tiny leaks**, “pinhole leaks” before losing significant refrigerant will prevent structural failures, reduce wear and tear. **Assuming an overall 35% leak reduction.**
 - Regular, proactive inspection of your AC unit can reduce refrigerant leaks and associated loss by 30% to 50% annually, according to industry experts and data referenced by the USA Department of Energy³⁰
 - Assumed certificate available after major service for proof AC system has been checked in the last 2 years. No additional costs.

²⁷ <https://www.buyautosupply.com/products/bas03045-1234yf-service-cap-m10x0-75-long-high-side?variant=43328017170525>

²⁸ Inspection / condenser cleaning where components are easily accessible. Where components are not accessible without extensive part removal, relying on AC Health monitoring is compulsory

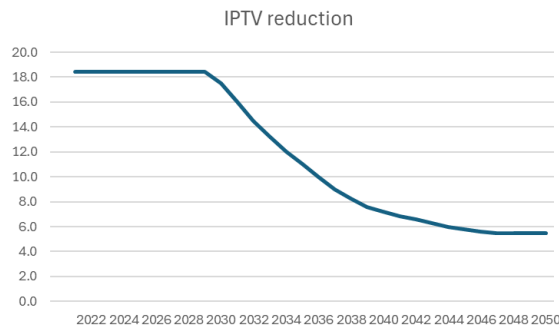
²⁹ France: <https://vantastic.fr/en/garage-labor-rates-in-2025-average-prices-and-advice/>

Hourly rates in Germany are significantly higher: <https://www.garagewireurope.com/news/workshop-costs-and-hourly-rates-in-germany/>

³⁰ <https://facilio.com/blog/hvac-refrigerant-leak-rate-calculation/#:~:text=Preventive%20maintenance%20is%20your%20first,and%20repair%20standards%20are%20met.>

Measure 3: With “SAE Style” Condenser Design Standard

- Over time (post 2030), reduce IPTV from 18.4 to ~5 (at average 11.3-year age when full fleet conversion has been completed).
- Combined impact of measure 1 & 2 driving IPTV to ~5
 - Cost impact: <20 €/vehicle during lifetime



Measure 4: AC Health Monitoring, “SAE Style” Standard

- Notice AC performance deterioration earlier
- Prevent more significant losses of refrigerant (via service notification)
- Doesn't completely prevent loss of charge, but reduces the risk of full charge losses significantly (vs 2024 data):
 - On average, **charge loss can be limited to 125g max or ~25% of charge** (of cases identified in 2024 as full charge loss)
 - Full charge losses still happen, but are more aligned with warranty data (e.g. 0.1 IPTV relating to stone damage results in 26k incidents in EU/year resulting in <15MT emissions)
 - Cost impact: ~<5 Euro/vehicle during lifetime

Measure 5: Tethered AC System Caps

- Mandate tethered cap
- Contributes to Assuming an overall 35% leak reduction (measure 1).
- Increases the leak integrity of the vehicle charge port
 - First fill
 - Retrofit during AC service
- Check during roadworthiness testing that caps are fitted (to pass the test)
- Cost impact: <1 €/vehicle during lifetime

Emission Reduction Scenarios (2030–2050)

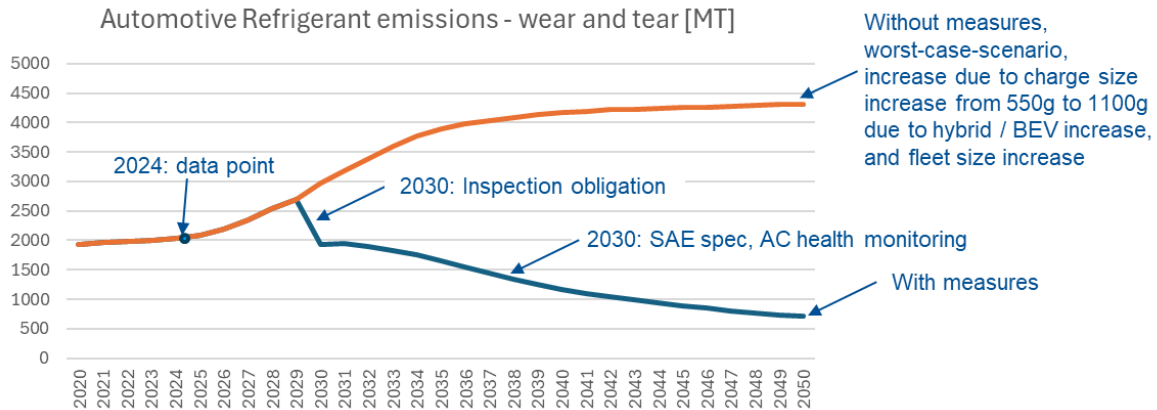
Emission Reduction Scenarios Based on Potential Legislative Measures by 2030

The baseline refrigerant emission scenario (orange line in below graph) is based on the 2024 data point that is scaled with the increase in charge size projection until 2050 and overall fleet increase (see chapter related to vehicle design). The baseline shows a significant increase in overall refrigerant emissions until 2050.

The “with measures” refrigerant emissions scenario (blue line in below graph) contains two phases.

- From 2030, an immediate ~35% drop can be observed. This is related to the obligatory increased detection measures (AC check & visual inspections using UV dye during major service and roadworthiness testing as well as the condenser cleaning during major service and the requirement for a tethered service port cap)

- Between 2030 and 2050, the additional measures regarding the condenser robustness specification, AC Health monitoring are gradually introduced into the fleet via new vehicle production.



Total amount of emissions saved (2030-2050) and cost effectiveness

Workstream	Category	Measure (Entry Into Force, Jan 1 st , 2030)	New vehicle production			Existing vehicles		Additional cost in € / vehicle lifetime
			ICE	Hybrid	BEV	ICE/Hybrid	BEV	
Repair	Design robustness	Compliance to new condenser robustness design specification, similar to SAE J2842 (to be developed)	Yes	Yes	Yes	-	-	<20
	Inspection	Obligation for UV Dye inclusion, SAE J2297	First fill	First fill	First fill	At service	At service	<1
		Compulsory for each major service (e.g. oil/break fluid change) typically ~2 years: AC check & visual inspection (UV dye) & requirement to repair, AC condenser water cleaning & debris clearing. Inspection certificate to be issued for road worthiness test inspection.	-	-	-	Yes	Yes	<200
		Verify the AC check & visual inspection and condenser cleaning have been carried out in the last two years during road worthiness testing (verify inspection certificate).	Test at factory	Test at factory	Test at factory	Yes	Yes	
Ongoing monitoring	AC system health monitoring, according to industry design specification (to be developed)	Yes	Yes	Yes	-	-	<5	

The repair workstream additional measures are relatively low in cost and are estimated to be <230€/vehicle. As these measures are focused on early detection of leaks and ensuring the AC system is well maintained, it will result in the significant reduction of the risk of a component failure and thus an extension of component life. Therefore the overall costs of these additional measures is likely going to be compensated by the increased component life expectancy. A compressor failure can easily cost > €3000/repair/vehicle, compensating the ~226€/vehicle additional measures.

In total, the baseline emission scenario 2030-2050 results in 83,774MT cumulative refrigerant emissions. The scenario including regulatory measures results in 26,544MT cumulative refrigerant emissions from 2030-2050 which is offering an overall reduction of 68% versus the baseline.

Services

Workstream Description, Data Set Used, Refrigerant Emissions

Services related refrigerant emissions can be divided into two main categories:

- 1) **RRR machine** (Recover, Recycle, Recharge) related refrigerant emissions, these will be covered in this workstream.
- 2) **Refrigerant emissions due to leaks not being repaired.** In EU, it is common to “top-up” a vehicle that is lacking in cooling from the air conditioning (A/C). This means that when a customer takes their vehicle in for service, the garage will just add more refrigerant to their vehicle. If there happens to be a leak in the system, refrigerant will continue to leak into the environment. These emissions are considered to be part of the design leak work stream.

Description of Data Sets Used

Data set 1: RRR Machine Related Refrigerant Emissions

An A/C RRR machine (Recover, Recycle, Recharge) is an automotive service unit designed to remove old refrigerant, clean it, and refill vehicle A/C systems to precise manufacturer specifications. These units automate the handling of R134a or R1234yf refrigerants, ensuring SAE compliance in the US, vacuum leaks checks, and accurate oil recharging.

- 1. **Recovery:** The machine extracts refrigerant, filtering it and separating oil, with recovery efficiencies often exceeding 95% (on in the United States per SAE J2788).
- 2. **Recycle/Vacuum:** The machine cleans the refrigerant and creates a vacuum in the system to remove moisture and contaminants.
- 3. **Recharge:** The system is refilled with the precise amount of refrigerant and oil, often within ± 0.5 oz of accuracy.

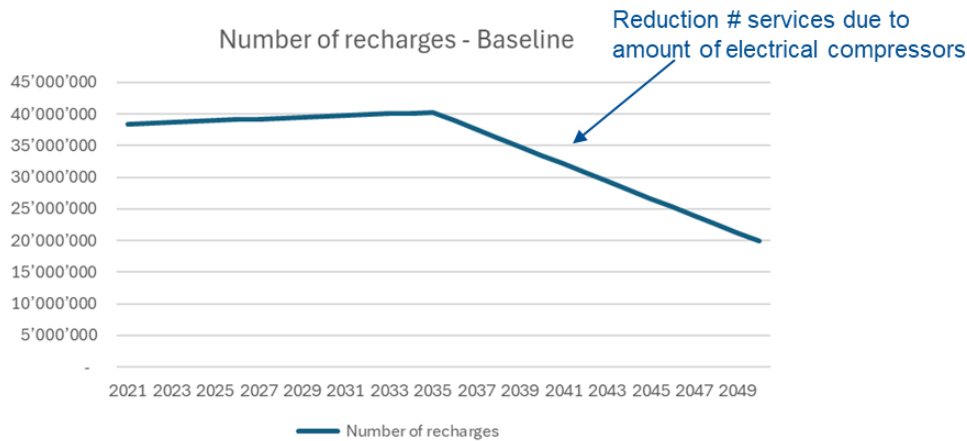
During this process, meetings were conducted with 3 well-known, reputable RRR machine suppliers in both the EU & US. During these discussions, it was learned that SAE International, in the USA, has standards where the RRR machines have to recover at least 95% of the refrigerant in the system, per SAE J2788. The EU doesn’t have regulations for RRR machines, and the ones used in this region recover only approximately 80% of the refrigerant. It is currently estimated that ~90% of the service machines in the EU can meet a recovery efficiency exceeding 95% with the remaining machines achieving ~80% recovery. As machines with lower recovery rate are significantly cheaper, this part of the market is expected to more than double by 2030 (hence to >20%).

Analysis Methodology and Assumptions Used

The workstream on vehicle design describes the calculation method to determine the total amount of services required per year* (baseline and additional legislation scenarios).

# Services	Baseline (ICE 14%, BEV 9%, leak rate 2050: 10.25g/vehicle)		
	2021	2035	2050
Without repair	38'446'764	40'300'505	19'873'595

# Services	Improved (ICE 11%, BEV 7%, leak rate 2050: 6.5g/vehicle)		
	2021	2035	2050
Without repair	38'446'764	-	-
With repair	-	20'695'719	8'264'750



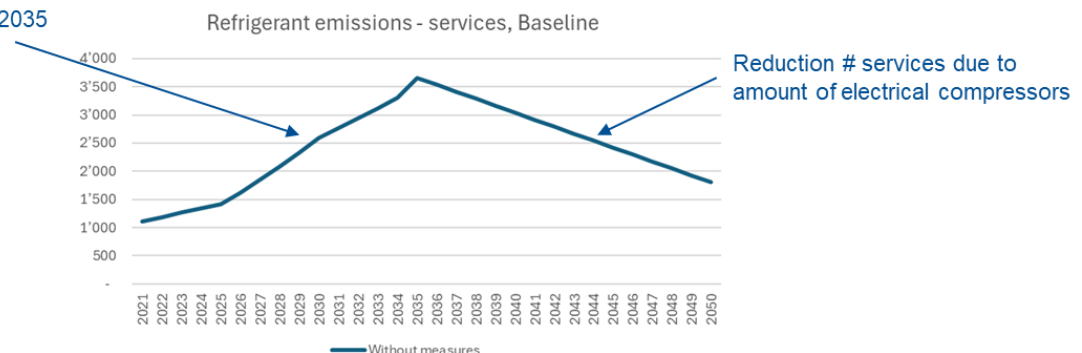
Using the design architecture emission model, calculations for 2021, 2035 and 2050 where 2030, 2040 and 2045 are determined via linear interpolation.

Baseline Emissions

Emissions increase as the charge size increases and as the proportion of lower recovery rate RRR machine increases.

- Service garages will need to invest in new R-1234YF RRR machines as the amount of vehicles using R-1234YF will continue to increase. If there is no control over the type of RRR machine that can be used (95% recovery rate versus 80%), there is a risk that cheaper machines with lower recovery rates (~80%) are purchased. This will lower the amount of refrigerant recovered and increase the amount of refrigerant emitted.
- It is estimated that the proportion of RRR machine with low recovery rates in the EU will increase from 10% in 2021 to 30% by 2035. The recovery rate in 2021 is estimated to be approximately 93%, and this rate could go as low as 89% from 2035

Increase in charge size, low recovery RRR machine share from 10% to 30% by 2035



Legislative Measures

Potential Legislative Measures by 2030, Description, Feasibility Affordability

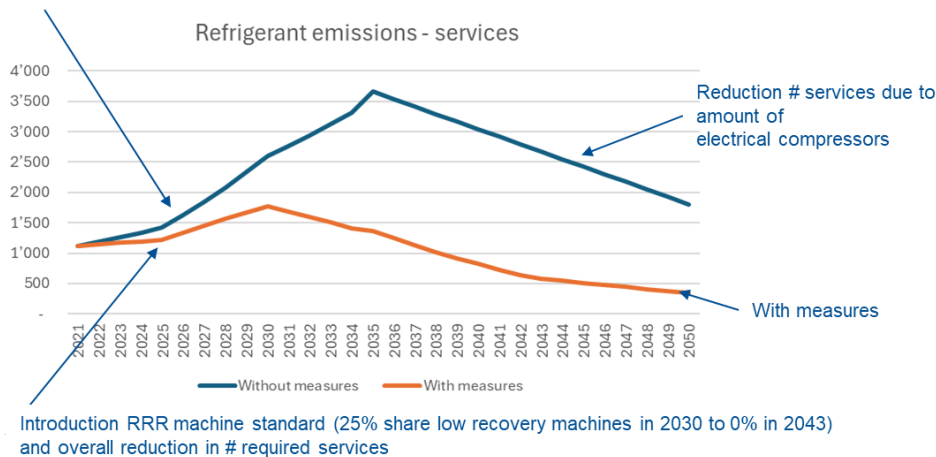
Measure 1: Recover Rate of RRR Machines >95%

- **All RRR machines sold in the EU from 01/01/2030 need to be certified SAE J2788 or SAE J2843 compliant or transpose these standards into European standards**
 - **Feasibility:** Machines are available on the market to purchase.
 - **Affordability:** The average cost difference between a high quality and a low-quality machine is estimated to be EUR 1,350. 66,000 additional high-quality machines would need to be purchased between 2030 and 2050, representing an additional investment of EUR 89M for the entire value chain over 20 years.

Measure 2: Refrigerant Recovery Monitoring

- To ensure the full reporting and traceability of all recovered refrigerant, a reporting system needs to be in place that also allows and encourages the possibility to report the refrigerant that is reused or sold.
- **This could be handled through the implementation of a refrigerant digital logbook.**
- This reporting is already compulsory under the F-gas regulation for all equipment with a charge above 1kg. This measure would simply extend the reporting obligation to all motor vehicles.
 - **Feasibility:** Good feasibility since the data on recovered refrigerant is stored in the RRR machines
 - **Affordability:** The only cost is the development of an electronic logbook and the centralization of the data, which cost can be spread over all the users of such a logbook.

Increase in charge size, low recovery RRR machine share from 10% to 30%



2030-2050 overall refrigerant emission reduction versus “without measures” ~67%

End-Of-Life

Workstream Description, Data Set Used, Refrigerant Emissions

The end-of-life workstream estimated the emissions of refrigerant during the vehicles end-of-life process. To estimate the amount of refrigerant emitted during the end-of-life process, the focus is on data gathering on the amount of refrigerant that is recovered at end of life. As vehicles are depolluted, which is mandatory before further treatment as per the End of Life of Vehicle directive (ELV)³¹, the refrigerant is removed with a specialized machine called a refrigerant RRR machine (Recovery, Recycling, and Recharging machines). RRR machines have the capability to recover a large

³¹ <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32000L0053>

part of the refrigerant in a mobile air conditioning system, but not its entirety. What remains in the vehicle after depollution can be considered as emissions.

As mentioned in the Annex XV report, F-gases are the only substances within scope that already have a legal obligation/incentive to be recovered and then either recycled, reclaimed, or destroyed³² (as per Article 8 of the F-gas Regulation). Recycling is a basic cleaning process for reuse mainly done by installers,³³ whereas reclamation - a more sophisticated reprocessing with a quality guarantee³⁴ - is done by professional reclamation companies. The quantities of F-gases being recycled and reclaimed has increased substantially since the current F-gas Regulation entered into force (*i.e.* the quantities reported as reclaimed HFCs increased from 377 tonnes in 2014 to 1,026 tonnes in 2021).³⁵ Recycled and reclaimed F-gases also have specific labelling requirements.

In this section, the specific provisions of the current F-Gas Regulation are analysed and other European regulations aimed at preventing F-gas emissions at the end of life.

F-gases are already strictly regulated under the current Regulation 2024/573 ("F-gas Regulation")³⁶. Additionally, there is other EU legislation, which in a greater or lesser degree, relate to the management of F-gases. In this regard, as it will be seen below, the rules in those pieces of legislation are complementary to the F-gas Regulation and contribute to the objective to manage and minimize emissions of F-gases, which is, in essence, the objective of the PFAS restriction proposal. This occurs in our case by establishing requirements for the end-of-life of vehicles.

EU and National Regulatory Framework

F-Gas Regulation: Provisions in the Current Regulation

Prevention of emissions at the end-of-life. Besides the emissions occurring during the use phase of F-gas-containing equipment, the end-of-life of this equipment present another potential source of F-gas emissions. Therefore, the current F-gas Regulation sets out legal requirements for the recovery, recycling, reclamation and destruction of F-gases for operators of equipment. Importantly, a key benefit of F-gases is their circularity, *i.e.*, their ability to be reclaimed, recovered, recycled and reused in new applications.

Under the current regime, operators of stationary equipment or of refrigeration units of refrigerated trucks and trailers containing F-gases must ensure that the recovery of those gases is carried out by the natural persons that hold the relevant certificates, so that these gases are recycled³⁷. Therefore, the operators of such equipment must recover the F-gases in all cases, which additionally need to be carried out by a certified person.

For operators of other equipment (such as Mobile Air Conditioning (MAC) equipment for passenger cars), the F-gas regulation states that the recovery of the F-gases must be performed "*unless it can be established that it is not technically feasible or entails disproportionate costs*"³⁸. After the recovery, F-gases are recycled, reclaimed or destroyed. Only personnel with a training certification are

³² Annex XV Restriction Report Proposal for a restriction for per- and polyfluoroalkyl substances (PFASs), p. 42;

³³ Article 3(12) F-gas Regulation;

³⁴ Article 3(13) F-gas Regulation,

³⁵ ETC CM report 2022/3 Fluorinated greenhouse gases 2022, available at <https://www.eionet.europa.eu/etcs/etc-cm/products/etc-cm-report-2022-03>;

³⁶ Regulation (EU) 2024/573 of the European Parliament and of the Council of 7 February 2024 on fluorinated greenhouse gases, amending Directive (EU) 2019/1937 and repealing Regulation (EU) No 517/2014: <http://data.europa.eu/eli/reg/2024/573/2024-02-20>

³⁷ Article 8(1) F-Gas Regulation;

³⁸ Article 8(10) F-Gas Regulation;

considered appropriately qualified for the recovery of these gases from air-conditioning equipment in motor vehicles (*i.e.* those under the scope of the MAC Directive).³⁹

Prevention of emissions at the end-of-life. The scope of the mandatory recovery obligation of stationary equipment is expanded to also include certain types of mobile equipment: "(a) the cooling circuits of refrigeration units of refrigerated trucks and refrigerated trailers; (b) the cooling circuits of refrigeration units of refrigerated light-duty vehicles and intermodal containers, including reefers, and train wagons; (c) the cooling circuits of air-conditioning equipment and heat pumps in heavy duty vehicles, vans, non-road mobile machinery used in agriculture, mining and construction operations, trains, metros, trams and aircraft."⁴⁰

End of Life Vehicles Directive

Directive 2000/53/EC on end-of-life vehicles ("ELV Directive") lays down measures on how vehicles should be treated at the end-of-life, with a focus on the reduction of disposal of waste and the increase of reuse, recycle and other forms of recovery of end-of-life vehicles. In this regard, it is considered that the provisions under the ELV Directive are complementary to the F-gas Regulation and provide additional information on how to manage and treat end-of-life vehicles. Especially:

- Recovery under the F-gas Regulation means "*the collection and storage of F-gases from containers, products, and equipment during maintenance or servicing or prior to the disposal of the containers, products or equipment*".⁴¹
- Treatment under the ELV Directive means any activity after the end-of life vehicle has been handed over to a facility for depollution, dismantling, shearing, shredding, recovery or preparation for disposal of the shredder wastes, and any other operation carried out for the recovery and/or disposal of the end-of life vehicle and its components.⁴² Annex I to the ELV Directive provides the minimal technical requirements for treatment of ELV. In particular, as regards operations for depollution, operators must remove, separate collect and store the air-conditioning system fluids and any other fluid contained in the end-of-life vehicle.⁴³ For the depollution of the ELV, the fluids must be removed using specialist equipment and transferred to a collection cylinder.

It is also noted that the depollution activities involve air-conditioning system fluids, which tend to be F-gases. Therefore, it can be concluded that most AC fluids (as referred to Annex I(3) to the ELV Directive) are also subject to the F-gas Regulation.

The definitions of depollution of ELV (*i.e.* removal, separate collection and removal of the AC fluids) and recovery of F-gases are technically similar and entail comparable actions to carry out by the operator. The F-gas Regulation provides additional obligations as regards the recovery of F-gases from passenger vehicles (for example, as regards the training requirement for the operator when recovering the F-gas). In any event, the measures provided in the ELV Directive, applied in combination with the F-gas Regulation, provide an effective and appropriate framework to manage the emissions of refrigerants at the end-of-life. This is confirmed by the approach taken by Member State authorities (e.g. Ireland for which national guidance for recovery of air conditioning system fluids from ELVs⁴⁴ addresses both pieces of legislation together).

³⁹ Article 8(4) F-Gas Regulation;

⁴⁰ Article 8(3) F-Gas Regulation;

⁴¹ Article 3(11) F-Gas Regulation;

⁴² Article 2(5) ELV Directive. Please note that the meaning of recovery in the ELV Directive differs from the F-Gas Regulation;

⁴³ Annex I(3) ELV Directive;

⁴⁴ Environmental Protection Agency, Recovery of Air Conditioning System Fluids from ELVs at Authorised Treatment Facilities and Metal Shredder Sites, available at: [https://www.epa.ie/publications/compliance--enforcement/air/ods--f-gas/Removal-of-Air-Conditioning-Gases-at-Authorised-Treatment-Facilities-and-Waste-Shredder-Sites-\(EPA,-v1-Jan-2022\).pdf](https://www.epa.ie/publications/compliance--enforcement/air/ods--f-gas/Removal-of-Air-Conditioning-Gases-at-Authorised-Treatment-Facilities-and-Waste-Shredder-Sites-(EPA,-v1-Jan-2022).pdf);

The ELV Directive is currently under revision. On 13 July 2023, the Commission published a proposal for a Regulation on circularity requirements for vehicle design and on management of end-of-life vehicles ("ELV Regulation Proposal")⁴⁵, which would replace the current ELV Directive and become directly applicable in all Member States. The ELV Regulation aims to prevent and reduce the adverse impacts from management of end-of-life vehicles and to ensure a high level of protection of human health and the environment.

Given the change of legal instrument (from a directive to a regulation), the proposal will harmonize the national legal requirements on the management of end-of-life vehicles. In particular, the minimum treatment requirements for depollution operations are further specified that in the ELV Directive (which are currently implemented by national laws), thus clarifying the steps for the recovery of the F-gases contained in vehicles.

In this regard, the operators must carry out the depollution operations as soon as possible after its delivery to the authorized treatment facility (ATF).⁴⁶ Annex VII specifies that (1) fluids and liquids contained in ELV such as air-conditioning system fluids must be removed from the ELV unless they are necessary for the re-use of the parts concerned;⁴⁷ and (2) parts, components and materials such as air conditioning systems and refrigerants must be treated in accordance with the F-Gas Regulation.⁴⁸ Additionally, it states that all parts, components and materials collected during the depollution shall be stored in designated containers.⁴⁹ It also further specifies that the collection containers in which the AC systems fluids/AC systems/refrigerants are collected must be accordingly labelled and stored in a secure location, in order to prevent accidental spillage, leakage or unauthorized access to it.⁵⁰

The proposal also provides information obligations for car manufacturers, which must provide waste management operators, and repair and maintenance operators access to information enabling a safe removal of parts, components and materials which contains fluids and liquids and are contained in vehicles.⁵¹

Therefore, the ELV Regulation explicitly reinforces the complementarity (and coherence) between this piece of legislation and the F-gas Regulation, being the measures providing a correct and sufficient framework to manage the emissions of refrigerants at the end-of-life.

It should be noted that the ELV Regulation proposal will follow the ordinary legislative procedure, which is expected to last, at least, several months.

As an example, here are the national transposition of the ELV directive into two of the 3 Belgium autonomous regions: Flemish region and Brussels region

Transposition into the Flemish region legislation:

Summary of Relevant VLAREMA Provisions: – Decree of the Flemish Government establishing the Flemish Regulation on the sustainable management of material cycles and waste (End-of-life Vehicles – Articles 5.2.4.3 §4 & §8 and 5.2.4.4 3°)

⁴⁵ https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles_en Proposal for a Regulation of the European Parliament and of the Council on circularity requirements for vehicle design and on management of end-of-life vehicles, amending Regulations (EU) 2018/858 and 2019/1020 and repealing Directives 2000/53/EC and 2005/64/EC.

⁴⁶ Article 29 ELV Regulation Proposal;

⁴⁷ Annex VII(B)(1) ELV Regulation Proposal;

⁴⁸ Annex VII(B)(2) ELV Regulation Proposal;

⁴⁹ *Ibid.*;

⁵⁰ *Ibid.*;

⁵¹ Article 11 ELV Regulation Proposal;

Within the Flemish regulatory framework for the sustainable management of end-of-life vehicles, authorized treatment facilities play a central role in ensuring that vehicles are dismantled, processed, and recycled in an environmentally responsible manner. According to Article 5.2.4.3, these centers must not only carry out depollution and dismantling activities, but they are also required to meet specific performance and reporting obligations that support the broader system of producer responsibility.

To begin with, each recognized treatment centre must achieve the legally defined reuse and recovery targets associated with the acceptance obligations imposed on vehicle producers. To support this process, producers—or the organizations acting on their behalf—provide the treatment centres with detailed information about the recovery rates already attained. The facilities must in turn demonstrate the final destinations of all recovered materials, ensuring that traceability is maintained throughout the recycling chain. When materials are transferred to parties that do not require an environmental permit, the centres are still obligated to hand them over only to companies that use the best available techniques, thereby guaranteeing high environmental standards even outside the permitting system.

These facilities also bear comprehensive reporting responsibilities. Upon explicit request from OVAM, the Flemish waste authority, a centre must submit a complete overview of the flow of vehicles and materials processed at the site, expressed in kilograms. This includes detailed lists of all incoming end-of-life vehicles, categorized by type and accompanied by their total weight and chassis numbers. Similarly, the centre must account for all outgoing vehicles using the same criteria. Moreover, it must report on every category of material leaving the facility, specifying the quantity and identifying the destination to which it was sent. These obligations ensure transparency and allow the authorities to maintain oversight of the material lifecycle from the moment a vehicle becomes waste through to its final reuse or disposal.

In addition to the operational obligations outlined above, Article 5.2.4.4 describes the criteria that individuals must meet in order to be recognized as competent to carry out specialized tasks within these facilities. One such requirement concerns anyone responsible for recovering fluorinated greenhouse gases from vehicle air-conditioning systems. These individuals must hold an officially recognized technician certification in accordance with the provisions of the VLAREL regulatory framework. A temporary exception is permitted for those who have enrolled in the required certification program: for up to one year from the date of enrolment, they may perform recovery tasks provided they do so under the supervision of a fully certified technician. This provisional period ends as soon as the individual obtains certification. This requirement ensures that the handling of environmentally harmful substances is performed safely and competently, aligning with EU-wide minimum training standards for F-gas recovery.

Transposition into the Brussels region legislation:

Summary of the key content of the Arrêté du Gouvernement de la Région de Bruxelles-Capitale du 1 December 2016 relatif à la gestion des déchets (published in the Moniteur belge on 13 January 2017).

The 1 December 2016 Brussels-Capital Region Government Order on Waste Management establishes a unified and modern legal framework governing the generation, handling, tracking, treatment, and reporting of waste across the region. It consolidates earlier waste rules and aligns Brussels with key EU directives on batteries, end-of-life vehicles, waste electrical and electronic equipment (WEEE), and the overarching EU Waste Framework Directive.

The Order opens with general provisions defining core concepts and clarifying its scope. It then introduces an extensive traceability and reporting system, obliging waste collectors, transporters, and treatment operators to document waste movements, maintain registers, and report information to Bruxelles Environnement, the regional environmental authority. These rules aim to ensure transparent oversight of waste flows and improve environmental compliance.

A central component of the regulation is its robust framework for Extended Producer Responsibility (EPR). Producers of goods that generate regulated waste streams—such as batteries, tyres, electronics, and vehicles—must organize or finance the collection, recycling, or recovery of the waste produced by their products. These rules apply equally to producers and to the approved bodies that manage EPR schemes. Obligations include recovery targets, treatment standards, public information duties, and periodic reporting requirements.

The Order also lays out detailed requirements for various waste operators, including collectors, transporters, brokers, and treatment facilities. These actors must comply with permitting requirements, keep accurate documentation, and ensure that waste is managed in line with safety and environmental protection standards. The text incorporates pre-existing rules on hazardous waste, incineration, and international waste shipments, harmonizing Brussels' waste management with EU Regulation 1013/2006 on waste transfers and environmental permit provisions.

In addition to general obligations, the legislation dedicates entire sections to specific waste streams, including batteries, waste oils, end-of-life vehicles, and WEEE. These stream-specific obligations reflect regional waste-prevention priorities, requiring operators to maximize reuse, recycling, and recovery while minimizing landfill disposal.

Authorized Treatment Facilities (ATF):

Febelauto⁵² – the Belgian organisation responsible for the management of end-of-life vehicles (ELVs) is responsible for the correct treatment of all vehicles arriving at the end of their life and their waste streams. There are at least 16 organisations in Europe that deal with end-of-life vehicles.

Febelauto has defined its own standards⁵³ (based on legislation), which the Authorized Treatment Facilities (ATF) that are part of their organization need to comply with.

These cover:

- 1) The approval procedure to become and remain an Authorized Treatment Facility (ATF)
- 2) How to transport and store vehicles and the various waste streams
- 3) Technical equipment and permits required for vehicle decontamination and dismantling and destruction.
- 4) Treatment methods for each waste stream
- 5) End-of-life vehicle monitoring system developed by Febelauto—known as the EMS (“End-of-Life Vehicles Monitoring System”) — An extranet application made available free of charge to ATFs, enabling the centralized recording and overall management of all data relating to the treatment of end-of-life vehicles in Belgium.
- 6) Administration; including
 - a. Annual audit: The report of the annual audit review must be submitted annually to the authorities
 - b. Waste registry: An approved facility is required to maintain a waste register in which all entries and exits are recorded on a day-to-day basis.
- 7) Training, specifically for the handling of F-gases Link to the OVAM⁵⁴ (Public Waste Agency in the region of Flanders (Belgium)) Video on the depollution of vehicle air conditioning systems: <https://www.youtube.com/watch?v=p6wk3hExXaE>
- 8) Guidelines around the transport of vehicles for destruction.

⁵² <https://www.febelauto.be/fr/>

⁵³ https://www.febelauto.be/public/normes_febelauto_v15_avril_2024_final.pdf

⁵⁴ <https://ovam-english.vlaanderen.be/>

Recovered Refrigerant Data in 2021 (Belgium & Netherlands)

Description Of Data Sets Used

Data set 1: End of life of vehicle statistical information

Statistical information⁵⁵ on end-of-life vehicles in the European are based on Directive 2000/53/EC⁵⁶ on End-of-Life Vehicles and Commission Decision 2005/293/EC⁵⁷, which lays down rules on monitoring the reuse/recovery and reuse/recycling of end-of-life vehicles according to the definition of these operations in Directive 2000/53/EC. EU and EEA/EFTA countries report data annually on the total vehicle weight and number of end-of-life vehicles and rates for 'total reuse and recycling' and 'total reuse and recovery'.

The total number of end-of-life vehicles reported in the European Union was 5.683 million in 2021 representing 6,535,000 tonnes.

Data set 2: Recovered refrigerant statistical information

Two end of life of vehicles producer responsibility organisations (PRO) shared the amount of refrigerant recovered in our baseline year, 2021:

- Febelauto⁵⁸, the Belgium PRO treated 103,659 vehicles in 2021
- ARN⁵⁹, Auto Recycling Netherlands treated 178,180 of the 197,046 vehicles treated in the Netherlands in 2021. All the information provided by ARN has been scaled to represent the total amount of vehicles treated in the Netherlands in 2021.

Both associations were able to share information on the amount of refrigerant recovered in 2021. These amounts can be used to estimate the amount of refrigerant that can be recovered in the EU if the process used by each PRO, or similar processes are also in place in the other EU countries or can be put in place by the other EU member states.

Methodology for EU-Wide Extrapolation

Analysis Methodology and Assumptions Used

To estimate the total amount of refrigerant recovered in the EU in 2021, it is considered that the vehicles treated in Belgium and the Netherlands as a proportion of the total vehicles treated in the EU.

The vehicles treated in Belgium in 2021 (103,659 vehicle) represented 1.82% of the total vehicles treated in the EU (table 1⁶⁰).

The vehicles in the Netherlands in 2021 (197,046 vehicles) represented 3.47% of the total vehicles treated in the EU.

⁵⁵ https://ec.europa.eu/eurostat/statistics-explained/index.php?title=End-of-life_vehicle_statistics#Number_of_end-of-life_vehicles

⁵⁶ <http://data.europa.eu/eli/dir/2000/53/2023-03-30>

⁵⁷ <http://data.europa.eu/eli/dec/2005/293/oj>

⁵⁸ <https://www.febelauto.be/fr>

⁵⁹ <https://arn.nl/en/>

⁶⁰ https://ec.europa.eu/eurostat/databrowser/view/env_waselvt_custom_19239152/default/table

Table 1: End-of-life vehicles generated, 2008–2023
(number)

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
EU (*)	5 079 000	7 700 000	6 213 000	5 555 000	5 123 000	5 065 000	5 043 000	4 968 000	4 823 000	5 300 000	6 105 000	6 074 000	5 370 000	5 683 000	4 667 000	4 265 000
Belgium	141 521	140 993	170 562	165 016	160 615	134 506	126 835	107 425	106 458	120 896	142 852	134 629	110 161	103 659	81 350	63 592
Bulgaria	38 600	55 330	69 287	62 937	57 532	61 673	80 862	85 946	92 706	102 442	99 835	85 670	68 635	87 362	95 084	105 268
Czechia	147 259	155 425	145 447	132 452	125 587	121 838	131 987	139 440	145 928	154 306	169 715	178 683	167 814	174 638	160 427	156 593
Denmark	101 042	96 830	100 480	93 487	106 504	125 650	104 413	98 929	89 039	117 124	117 519	119 551	95 084	104 515	83 305	74 369
Germany	417 534	1 778 593	500 193	466 160	476 601	500 322	512 163	473 386	412 801	506 531	560 455	461 266	406 044	396 773	292 877	250 749
Estonia	13 843	7 528	7 268	11 413	12 835	14 712	14 720	12 884	11 184	16 236	18 147	15 293	15 501	20 403	14 481	16 499
Ireland	127 612	152 455	158 237	134 960	102 073	92 467	86 950	74 910	98 213	140 788	162 521	149 445	118 867	145 628	105 494	90 413
Greece	55 201	115 670	95 162	112 454	84 456	86 205	82 863	87 050	46 573	39 761	47 141	49 533	44 759	53 516	53 740	55 097
Spain	748 071	952 367	839 637	671 927	687 824	734 776	724 820	689 760	611 446	620 055	748 306	813 768	713 404	727 270	637 210	601 607
France	1 109 876	1 570 593	1 583 283	1 515 432	1 209 477	1 115 280	1 084 766	1 016 326	1 046 083	1 138 742	1 571 776	1 623 522	1 331 185	1 345 831	1 168 225	1 029 932
Croatia (*)					35 213	32 135	19 388	16 900	20 386	21 074	27 404	40 892	46 919	32 929	33 048	24 940
Italy	1 203 184	1 610 137	1 246 546	952 461	902 611	876 052	853 584	958 245	978 960	990 876	1 030 318	1 094 731	1 002 401	1 172 305	797 046	737 852
Cyprus	14 273	17 303	13 219	17 145	17 547	13 212	11 160	8 293	5 151	5 453	7 523	10 170	9 367	9 851	7 830	7 309
Latvia	10 968	10 590	10 640	9 387	10 228	9 003	9 268	8 924	8 049	11 439	11 435	11 592	11 885	10 247	11 628	14 300
Lithuania	19 534	19 656	23 351	26 619	22 885	26 482	29 982	25 546	21 306	21 066	20 629	22 001	31 147	32 778	31 477	
Luxembourg	2 865	6 908	6 303	2 341	2 834	2 290	2 225	1 617	1 154	1 972	3 103	2 827	2 416	2 497	1 533	1 209
Hungary	37 196	26 020	15 907	13 043	15 357	14 897	15 283	16 788	15 141	15 573	19 280	20 743	19 526	17 614	16 934	15 156
Malta (*)			330	2 526	2 530	1 198	2 646	4 509	5 632	7 570	7 599	6 616	8 108	9 131	6 330	5 350
Netherlands	152 175	191 980	232 448	195 052	187 143	183 451	188 487	167 777	197 488	199 506	214 013	177 404	194 982	197 046	141 201	131 896
Austria	63 975	87 364	82 144	80 004	64 809	73 993	59 904	47 926	48 077	58 462	54 424	50 944	57 722	38 275	38 275	27 949
Poland	189 871	210 218	259 576	295 152	344 809	402 416	454 737	478 202	380 529	495 805	514 210	450 066	386 826	445 671	394 193	375 569
Portugal	107 746	107 946	107 419	77 929	92 008	92 112	86 713	84 158	88 559	99 910	107 140	111 112	101 378	117 997	109 538	101 315
Romania	51 577	55 875	190 790	128 839	57 950	37 989	42 138	41 886	46 572	49 830	67 344	84 621	79 360			
Slovenia	6 780	7 043	6 807	6 598	5 447		6 260	5 980	7 093	8 590	12 141	15 182	15 493	11 574	8 225	7 960
Slovakia	39 769	67 795	35 174	39 171	33 469	36 858	29 175	26 176	36 931	35 328	39 343	52 722	53 355	40 762	34 472	33 597
Finland	103 000	96 270	119 000	136 000	119 000	99 300	94 540	99 630	114 460	128 280	120 040	100 922	109 099	114 404	105 875	91 044
Sweden	150 197	133 589	170 658	184 105	185 616	189 748	186 967	188 810	186 875	192 395	204 458	186 370	175 748	171 576	157 981	134 177
Iceland (*)	9 386	5 109	4 195	4 075	5 824	4 463	5 245	6 063	6 527	9 483	11 392	11 635	10 927	9 624	8 165	8 163
Liechtenstein	91	72	107	94	114	326	188	230	260	326	213	180	195	131	12	31
Norway	130 018	95 000	112 537	124 563	119 905	141 452	139 920	145 098	142 280	143 664	143 767	144 933	138 203	129 222	117 067	105 444

(*) Data not available
(*) Eurostat estimates 2008-2011, 2013, 2021-2023.
(*) 2013 data: estimated.
(*) 2012 data: low reliability.
Source: Eurostat (online data code: env_waseht)

Another method to estimate the total amount of refrigerant recovered in the EU is by considering the weight of the vehicles treated in each of these countries as a proportion of the total weight of vehicles treated in the EU.

The weight of the vehicles treated in Belgium in 2021 represented 1.99% of the total vehicles treated in the EU (table 2⁶¹).

The weight of the vehicles treated in the Netherlands represented 3.22% of the total vehicles treated in the EU.

Data extracted on 06/03/2026 13:20:06 from [ESTAT]
Dataset: End-of-life vehicles - reuse, recycling and recovery, totals [env_waseht_custom_19044802]
Last updated: 09/12/2025 23:00

TIME	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
GEO (Labels)																
European Union - 27 countries (from 2)	4 789 000	7 108 000	6 096 000	5 540 000	5 109 000	5 332 000	5 279 000	5 217 000	5 130 000	5 708 000	6 758 000	6 909 000	6 156 000	6 535 000	5 463 000	5 047 000
Belgium	144 121	144 726	176 448	171 747	171 466	145 652	138 703	119 054	119 188	148 459	177 439	168 810	138 468	129 979	102 334	80 190
Bulgaria	38 600	63 027	74 422	65 428	59 191	62 723	82 258	88 066	92 111	104 457	103 032	88 372	73 521	90 127	102 324	106 718
Czechia	132 533	147 217	135 479	118 147	114 800	114 833	122 450	131 392	139 881	160 587	171 412	185 830	177 885	188 609	176 470	175 384
Denmark	101 173	99 515	104 866	100 816	114 392	128 869	118 597	109 762	100 957	134 331	136 717	143 357	113 150	129 055	101 839	92 248
Germany	387 693	1 596 831	516 128	468 459	475 719	490 771	502 656	474 379	420 113	530 311	595 761	501 658	456 586	444 590	327 862	283 549
Estonia	13 716	7 712	7 679	12 123	14 056	16 391	14 857	14 113	19 539	22 015	18 876	19 427	25 865	18 828	21 594	
Ireland	138 624	163 070	169 155	139 279	105 339	98 015	92 208	79 405	104 105	149 235	172 273	158 412	126 000	154 365	111 824	95 880
Greece	51 828	115 849	92 158	104 580	78 333	81 619	79 668	84 046	45 570	38 654	45 971	48 650	43 658	52 169	53 513	54 433
Spain	712 440	913 787	805 623	644 707	659 960	772 110	761 648	724 807	642 514	651 560	858 686	949 916	840 466	884 831	785 981	729 521
France	1 046 624	1 464 843	1 548 451	1 501 850	1 229 096	1 210 605	1 115 190	1 057 580	1 103 927	1 221 498	1 718 098	1 802 746	1 488 557	1 517 628	1 336 455	1 189 994
Croatia					33 221	29 017	22 584	19 617	18 912	24 662	30 616	45 677	53 033	37 807	39 838	25 953
Italy	1 106 929	1 379 027	1 240 204	986 391	874 887	959 542	953 690	1 036 562	1 086 425	1 086 145	1 201 500	1 292 768	1 223 053	1 404 154	1 013 939	971 292
Cyprus	12 703	15 400	11 764	15 259	15 617	11 759	10 468	8 152	5 094	5 159	7 267	9 926	9 030	9 595	7 720	7 914
Latvia	10 978	8 946	9 650	10 115	10 435	9 037	8 983	8 989	8 253	11 681	11 061	10 999	12 694	11 206	13 123	13 202
Lithuania	19 426	19 014	22 885	27 823	26 187	31 037	33 265	31 037	27 752	27 140	27 579	30 084	40 925	43 382	41 802	
Luxembourg	2 865	6 517	6 115	2 154	2 750	2 501	2 258	1 746	2 063	2 048	3 413	3 471	2 999	3 137	1 925	1 657
Hungary	28 287	27 419	15 589	14 959	14 388	14 865	13 887	13 380	12 527	14 249	15 925	21 858	20 613	18 490	18 164	17 068
Malta			288	2 225	2 177	1 050	2 835	4 803	6 322	8 182	7 425	7 096	8 350	11 324	8 332	10 238
Netherlands	146 316	187 296	232 239	198 173	191 260	189 138	196 215	174 152	204 400	206 489	223 216	186 629	208 631	210 248	151 367	142 843
Austria	52 202	74 211	67 997	67 384	56 180	65 475	53 310	43 934	45 338	57 065	61 149	53 576	50 940	59 293	39 623	28 703
Poland	170 100	192 281	217 636	284 307	340 212	401 639	462 202	493 468	395 216	522 299	551 221	555 826	440 183	517 179	463 347	444 753
Portugal	95 691	95 703	96 242	71 664	87 020	85 960	81 193	80 494	84 473</							

Vehicle Age, AC Penetration, and BEV Penetration

Vehicle Age Distribution at End of Life

Febelauto and ARN shared details of the vehicles recovered at end of life in Belgium and the Netherlands.

In the case of Febelauto, certain vehicles contained the first registration date, while others did not. The registration date was estimated for the vehicles that did not have a registration date by analysing the VIN numbers, the years the models were produced and assigning the remaining vehicles with no first registration date on a pro-rata basis.

In the case of ARN, only a limited number of vehicles did not have a registration date, and these were assigned on a pro-rata basis.

Both data sets provided the baseline for the vehicle age distribution at end of life. It is assumed that the vehicle age distribution through 2050 will stay the same as in the 2021 baseline.

The vehicle age distribution will also be kept constant when scaling the individual recovered amounts to the European level to determine the amount of refrigerant recovered and emitted in the EU in 2021.

Vehicle Air Conditioning Penetration

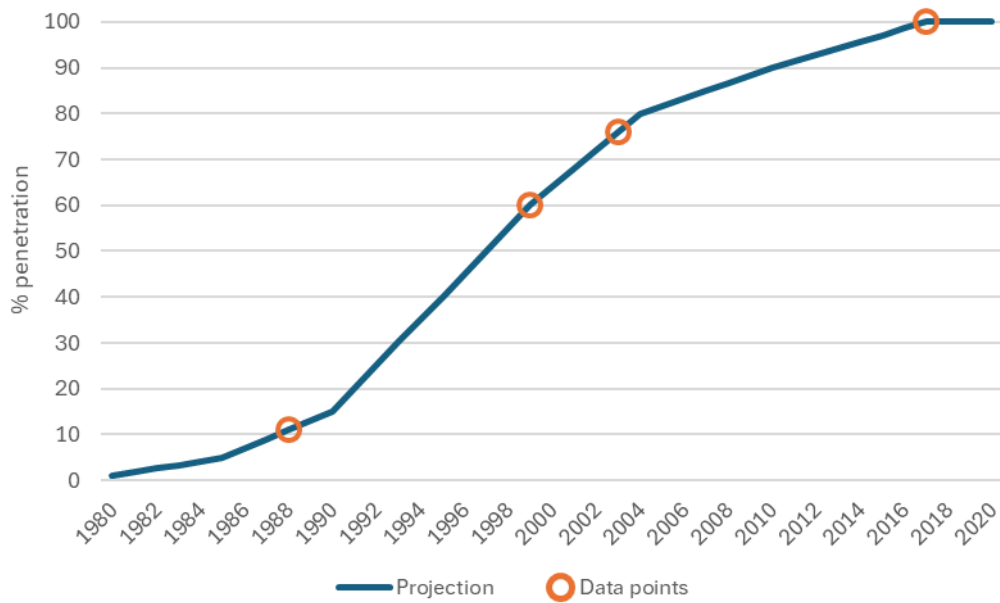
The level of penetration of air conditioning in the European market will have an impact on the amount of refrigerant that is recovered and emitted at the end of life. We used the following penetration assumption: The penetration rate of AC in the EU is estimated to be around 10% in the late 80's and around 60% in 1999⁶², 75% in 2003⁶³ and an assumption that 100% penetration was reached in 2017. It was estimated that in 2021, 72.5% of the vehicles in Belgium and 71.3% of the vehicles in the Netherlands that were treated at the end of life by the ATFs were equipped with an air conditioning system.

It is estimated that the AC penetration evolution using the 2021 vehicle distribution. In Belgium, by 2045 99.9% of the vehicles sent for destruction will contain an AC system. In the Netherlands, it is estimated that by 2043, 99.9% of the vehicles sent for destruction will be equipped with an air conditioning system.

⁶² <https://www.wardsauto.com/news/archive-wards-europe-cools-off-ac-on-60-of-new-cars-a-big-jump/763116/#:~:text=While%20the%20U.S.%20generally%20takes,Behr%20Group%2C%20a%20German%20supplier.>

⁶³ https://fr.wikipedia.org/wiki/Climatisation_de_v%C3%A9hicule_automobile

AC Penetration in the EU



Battery Electric Vehicle (BEV) Penetration

In battery electric vehicles (BEVs), traditional belt-driven air-conditioning (AC) units used for cabin cooling are replaced with alternative thermal management solutions such as heat pumps, which function as reverse AC systems capable of both heating and cooling. Instead of relying on a mechanically driven AC compressor, BEVs use a heat pump (HP) powered by an electric compressor. As a result, the heat pump in a BEV serves two essential purposes. It not only delivers the necessary climate-control functions for passenger comfort but also manages the thermal conditions of the battery. Continuous cooling of the battery is required to prevent thermal runaway—a condition that can generate smoke, fire, and in severe cases lead to uncontrollable combustion. Because heat pumps play such a crucial role in electric vehicles, they are considered safety-critical components that must meet high standards of reliability.

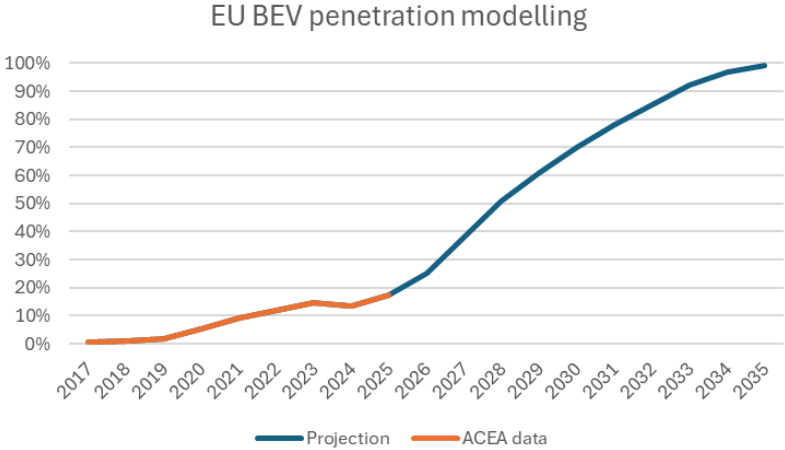
Battery performance, charging speed, and overall e-powertrain efficiency are heavily influenced by the external ambient temperature. Effective thermal management is therefore vital, as it directly affects customer-relevant factors such as driving range and cabin comfort—attributes that significantly shape brand perception among automotive manufacturers.

Maintaining proper battery temperature is essential not only for extending driving range but also for ensuring vehicle safety. If high ambient temperatures are combined with a heat pump operating at reduced capability, the battery pack may rapidly reach a dangerous temperature, increasing the risk of fire. When cooling becomes insufficient, the vehicle’s built-in safety systems may shut down operation entirely, potentially even while the vehicle is in motion.

It is estimated that a functioning BEV requires to have at least 75% of its original refrigerant charge. If the refrigerant level would reach a lower level, it is assumed that the vehicle would shut down and require a repair of the thermal management system and a top off of the refrigerant quantity before it can operate again.

As the penetration of BEVs increase, the amount of BEVs at end of life will also increase. For these vehicles to be in a functioning state, their level of refrigerant has to be at least 75%, which is significantly higher than the average amount of refrigerant recovered today at end of life. The data therefore needs to be adjusted to correctly reflect this increased refrigerant charge at end of life. A charge size of 1,100g for BEVs is assumed.

According to data from ACEA⁶⁴, 9.1% of the vehicles sold in the EU in 2021 were BEVs. To reach its climate neutrality goal by 2050, the EU is taking action to reduce emissions from cars as road transport accounts for one fifth of the EU’s CO2 emissions. The EU aims to cut emissions from cars 55% and from vans 50% by 2030, compared with 2021, in order to reach the goal of zero emissions from new cars and vans by 2035. This zero-emission goal would mean a penetration of BEVs of 100% no later than 2035.



Vehicle Fleet Evolution

As the age of the vehicles sent for destruction in the future years until 2050 cannot be predicted, it is assumed that the vehicle age distribution at end of life will remain the same as in the 2021 baseline year. The future recovered refrigerant and refrigerant emission is calculated keeping the vehicle age distribution constant for each year until 2050.

Accident Prevention Measures

As driving aids are popularized and implemented into the type of approval regulation⁶⁵, the accident rate will reduce. The number of vehicles that are sent for recovery at end of life, which have suffered catastrophic accident damage will also decline. In the vehicle accidents section, accident rates reduce by 36.9% between 2021 and 2050. The emissions linked to the accidents are captured in the vehicle accidents section. It is estimated that 50% of the vehicles that have suffered catastrophic accident damage retain their refrigerant charge (50% front end collisions, where the full charge is lost, 50% back-end collisions where the refrigerant charge is retained), the number of vehicles suffering catastrophic damage that are sent for destruction which retain their charge will reduce by 36.9% by 2050. The refrigerant that is recovered at end of life will reduce accordingly as well as the emissions linked to the recovery process.

It is estimated that all vehicles sent for destruction that are less than 11 years old are vehicles that have suffered catastrophic accident damage, and their number will be reduced by 36.9% by 2050 compared to 2021 in the base case scenario. This reduction rate has not been applied to the vehicles at end of life of an older age as it cannot be determined what proportion have suffered catastrophic accident damage.

⁶⁴ <https://www.acea.auto/files/ACEA-Pocket-Guide-2023-2024.pdf>
⁶⁵ <https://eur-lex.europa.eu/eli/reg/2019/2144/oj/eng>

Recovered Refrigerant in the EU

The recovered refrigerant will evolve throughout the period as the penetration rate of AC increases, as the penetration of BEVs increase and as the accident rate reduces and by keeping the same vehicle age distribution at end of life.

Emissions at End of Life in the EU

As vehicles are depolluted, the refrigerant is removed with a specialized machine called a refrigerant RRR machine (Recovery, Recycling, and Recharging machines). RRR machines have the capability to recover a large part of the refrigerant in a mobile air conditioning system.

The recovery rate (percentage of refrigerant recovered) will be dependent among other things, on the performance of the RRR machine used. Certain machines which meet the SAE J2788 (for R-134a machines) or J2843 (for R-1234yf machines) standards will recover more than 95% of the refrigerant in the vehicle if the correct recovery procedures are used. Other machines, which do not meet these SAE standards will recover less refrigerant. These machines recover only between 70% and 80% of the refrigerant remaining in the vehicle.

The volume of refrigerant emitted therefore depends on the amount of refrigerant left in the AC system of the vehicle and the recovery rate of the machine used.

With the phase out of R-134a and the introduction of R-1234yf in the early 2010's, the amount of vehicles containing R-1234yf that will be coming for destruction will increase, requiring ATFs to invest in new machines, as the R-134a recovery machines are not suitable to recover R-1234yf. If there is no control over the type of RRR machine that can be used, there is a risk that cheaper machines with lower recovery rates are purchased, which will lower the amount of refrigerant recovered and increase the amount of refrigerant emitted.

It is estimated that the proportion of RRR machine with low recovery rates in the EU in 2021 is approximately 10%. With the phase out of R-134a and the need to invest in new machines, this rate could go up to 50% as the ATFs try to optimize their investment in new equipment. The recovery rate in 2021 is estimated to be approximately 93%, and this rate could go as low as 85% from 2039 if no measures are taken to control the type of RRR machines that can be offered for sale in the EU.

Baseline and Future Emissions (2021–2050)

The emissions represent the amount of refrigerant left in the vehicle after the depollution process. This amount is dependent on the amount of refrigerant in the vehicle at end of life and the performance of the RRR machines used to depollute the vehicle.

This table details the refrigerant recovered in Belgium and the Netherlands and the extrapolation to the EU level by the two methods described in the methodology section as well as the emissions at end of life:

2021	Belgium	Netherlands
Recovered refrigerant (kg)	6,489	4,461 ⁶⁶
Number of vehicles treated	103,659	197,046
Proportion of EU vehicles	1.82%	3.47%
EU extrapolation recovered refrigerant (kg)	355,753	128,663
Estimated EU Emissions (kg)⁶⁷	26,777	9,684
Weight of vehicles treated (MT)	129,979	210,248

⁶⁶ Number of vehicles treated by ARN in the Netherlands in 2021: 178,180 vehicles

Amount of refrigerant recovered in 2021: 4,034kg

As a total of 197,046 vehicles were treated in the Netherlands in 2021, the amount of refrigerant recovered by ARN can be extrapolated to a total amount for the Netherlands in 2021: 4,461kg

⁶⁷ Emissions considering an average recovery rate of 93%

Proportion in the EU	1.99%	3.22%
EU extrapolation recovered refrigerant (kg)	326,250	138,662
Estimated EU Emissions (kg)⁶⁸	24,556	10,437

By using both calculation methods, the amount of refrigerant recovered in the EU in 2021 can be estimated to be between 355,753kg and 326,250kg using the amount refrigerant recovered in Belgium and between 128,663kg and 138,662kg using the amount refrigerant recovered in the Netherlands.

Based on the data available, a bracket of recovered refrigerant in the EU in 2021 can be estimated: Between 128,663kg and 355,753kg and the amount of refrigerant emitted in the EU in 2021: between 9,684kg and 26,777kg

This is a large bracket, but with the limited data available, a more precise value cannot be determined.

Extrapolating the estimated amount of refrigerant recovered in the EU by using the amount of refrigerant recovered in the Netherlands results in a lower extrapolation than using the amount of refrigerant recovered in Belgium.

Comparing the estimations, the differences could be due to a number of possible factors:

- The average age of the recovered vehicles
- The different reporting mechanisms
- The behaviour of the ATFs

Average age of recovered vehicles:

In Belgium the average age of the recovered vehicles in 2021 is estimated to be between 18 and 19 years old. In the Netherlands the average age of the recovered vehicles in 2021 is estimated to be between 19 and 20 years old. This average age difference of 1 year cannot explain such a difference in refrigerant recovery by vehicle.

Reporting mechanism:

In Belgium, each ATF is responsible for reporting into the software provided by Febelauto the amount of refrigerant that is recovered. This reporting also needs to describe the action taken by the ATF with the recovered refrigerant: for own use, resell the refrigerant to a certified technician or taken to a treatment facility.

In the Netherlands, ARN collects all the recovered material at the ATFs, and is responsible to report and treat the recovered material. If the ATF has the opportunity to sell the refrigerant or to use it to maintain a vehicle, as this refrigerant will not be collected by ARN, it will not be reported as recovered. This could explain that in the Netherlands, a certain amount of refrigerant might not report as recovered although it is reused in the maintenance of vehicles either directly by the ATFs or sold to garages for maintenance of existing vehicles.

ATF behaviour:

It is also possible that in both countries certain ATFs do not follow the regulations and that the refrigerant is illegally released to the atmosphere.

In the case of the Netherlands, the ATFs have no incentive to illegally release the refrigerant as the treatment of the refrigerant is not a financial burden to the ATFs, the cost of treating the refrigerant at end of life is covered by ARN.

⁶⁸ Emissions considering an average recovery rate of 93%

In the case of Belgium, it is the ATF's responsibility to properly handle the refrigerant that they do not sell or reuse and to bear any potential financial cost. The refrigerant is sent to the treatment facilities (Crealis and Cogal for example in Belgium) to be reclaimed or destroyed. Currently, with the financial value of reclaimed refrigerant, recovery companies are paying ATFs to recover their refrigerant in the case where the quality meets international quality standards (AHRI 700) for the recovered refrigerant to be treated and placed on the market. In the case where the refrigerant cannot be reclaimed to meet international quality standards, the recovery company will charge the ATF for the destruction of the refrigerant. It is possible that in rare cases this financial burden might encourage certain ATFs to take measures to not be burdened by potential destruction costs.

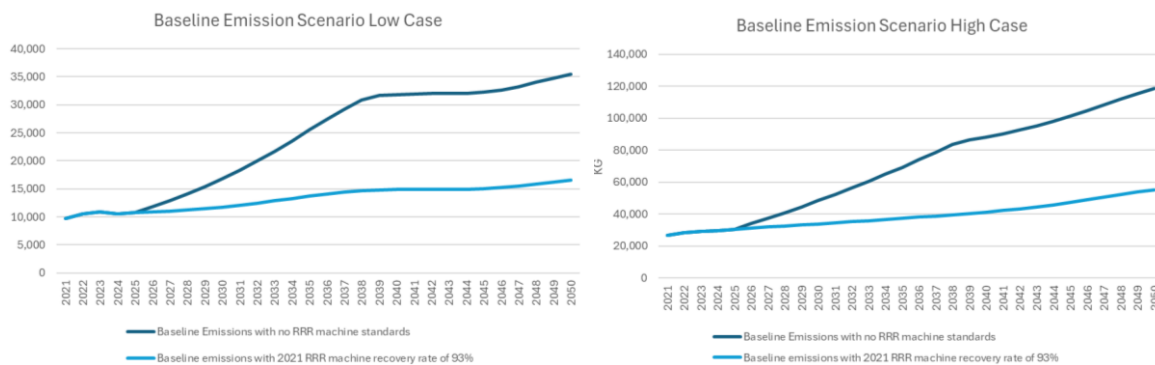
Extrapolation to 2050 of the Amount of Recovered and Emitted Refrigerant

Using the 2021 vehicle age distribution at end of life, the AC penetration, the increased BEV penetration, the reduction in accident rates impacting the vehicles suffering catastrophic damage and the degradation in the recovery rates due to the increased use of RRR machines with lower recovery rates the amount of refrigerant recovered in the EU in 2050 can be estimated:

	Low case	High case
2021 extrapolated recovered refrigerant (kg)	128,663	355,753
2021 AC penetration vehicles at end of life (%)	71.3	72.5
2021 BEV penetration at end of life (%)	0%	0%
2021 RRR machine average recovery rate (%)	93%	93%
2050 AC penetration vehicles at end of life (%)	100%	100%
2050 BEV penetration at end of life (%)	73%	76%
2050 Accident rate reduction on totalled vehicles (%)	36.9%	36.9%
2050 RRR machine average recovery rate (%)	85%	85%
2050 extrapolated recovered refrigerant (kg)	200,644	672,042

To estimate the amount of refrigerant emitted, the assumption around the change of the RRR machines average recovery rate is considered:

	Low case	High case
2050 extrapolated recovered refrigerant (kg) at 2021 RRR machine average recovery rate (93%)	219,528	735,293
2050 emissions at 2021 RRR machine average recovery rate	17,808	55,345
2050 extrapolated recovered refrigerant (kg) at 2050 RRR machine average recovery rate (85%)	200,644	672,042
2050 emissions at future RRR machine average recovery rate (85%)	35,408	118,596



The impact of the evolution of the RRR machines average recovery rate increases the 2050 EU refrigerant emissions between 18,884kg and 63,252kg.

Legislative Measures

Potential Legislative Measures by 2030, Description, Feasibility, Affordability

Recover Rate of RRR Machines

To limit the amount of refrigerant remaining in the vehicles after depollution (emissions), ensure that the best available technology is used for the recovery of refrigerants at end of life. All RRR machines sold in the EU from 01/01/2030 need to be certified SAE J2788 or SAE J2843 compliant or transpose these standards into European standards. This measure needs to be balanced with strict enforcement of refrigerant recovery, as with the increased investment into the machines, it is important that good practices continue to be followed.

Feasibility: Machines are available on the market to purchase.

Affordability: The average cost of a high quality RRR machine is around EUR 2,700. The average cost of a low quality RRR machine is around EUR 1,350. Reviewing the websites of the Producer Responsibility Organisations 2,248 ATFs treated 1,900,000 vehicles out of the 5,683,000 vehicles treated in the EU in 2021. By extrapolating this number, the total number of ATFs in the UE is estimated to be 6,700 ATFs

If an average life of an RRR machine of 10 years is considered, 6,834 additional high-quality machines would need to be purchased between 2030 and 2050, representing an additional investment of EUR 8,600,000.

Refrigerant Recovery Monitoring

To ensure the full reporting and traceability of all refrigerant recovered, a reporting system needs to be in place that also allows and encourages the possibility to report the refrigerant that is reused or sold by the authorised treatment facility. This monitoring can also encourage ATFs to purchase best in class recovery machines to ensure an optimal refrigerant recovery rate during depollution. This could be handled through the implementation of a refrigerant digital logbook that would enable full refrigerant traceability first fill, service, end of life, recovery & recycle/reclaim.

This reporting is already compulsory under the F-gas regulation for all equipment with a charge above 1kg⁶⁹. This measure would simply extend the reporting obligation to all motor vehicles (and require this to be via an electronic logbook). Already compulsory for over 1kg charge (F-gas regulation) so just extend. In addition, requirement for recovery and recycling/reclaim at end of life (EPR)

Feasibility: Good feasibility since the data on recovered refrigerant is stored in the RRR machines

Affordability: The only cost is the development of an electronic logbook and the centralization of the data, which cost can be spread over all the users of such a logbook, not only the ATFs.

⁶⁹ Article 5.1 F-gas regulation

Registration and Audit of Authorized Treatment Facilities

In both Belgium and the Netherlands, there are authorizations required to become an ATF. These are important to maintain an overview of the companies that will perform depollution activities. ATFs also need to be certified to perform the depollution activities and regular audits need to take place to ensure that good practices are followed. It is proposed that these requirements be written into the European regulation under REACH as condition of use and managed and funded at the national level to ensure that compliance and enforcement is coordinated by central national agencies. In the case of refrigerants, the audit procedure should focus on the amount of refrigerant that remains in the vehicle after depollution to ensure that best practices and best available technology are used to recover the refrigerant and reduce emissions.

It is the responsibility of the national authorities to allocate adequate resources to enforcement to ensure that the ATFs are in compliance with the legislative framework (through audits) and that the recovered refrigerant is also correctly reported and traceable (recovery monitoring).

Subsidy for Refrigerant Destruction

Promote the correct behaviour by ensuring that the treatment of the recovered refrigerant for destruction is not a financial burden to the ATFs: Use a recovery tax or an extended producer responsibility scheme (EPR) to pay for the destruction of refrigerant that cannot be brought back to a recognized quality specification (AHRI 700) to incentivize the ATFs to recover all refrigerant and send it for destruction if the refrigerant cannot be used.

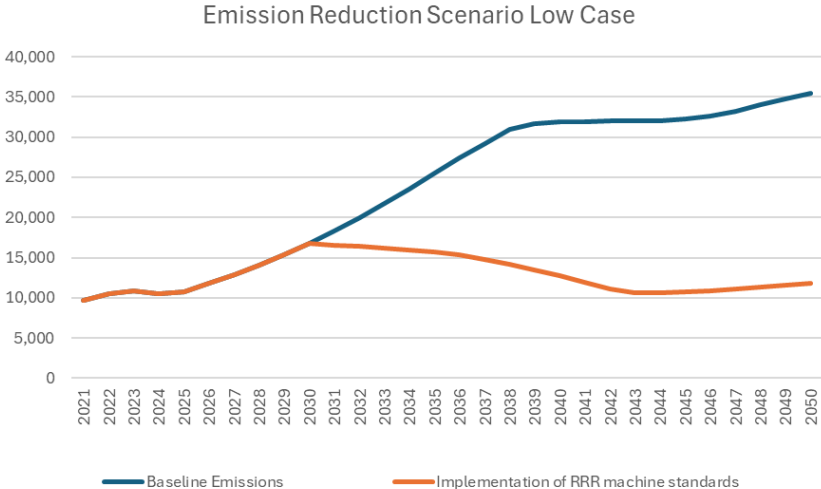
Potential Emission Reduction

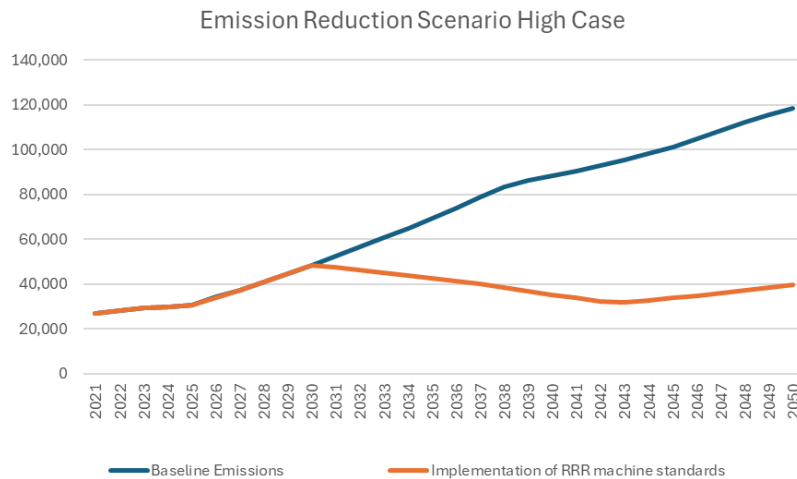
Emission Reduction Scenarios Based on Potential Legislative Measures by 2030

Legislative measures:

RRR machine standards: improving the average recovery rate from a forecasted 2050 rate of 85% to 95% and reducing the emission rate proportionally.

With the implementation of the RRR machine standards in 2030, the 2050 emissions at end of life can be reduced between 23,605kg and 79,064kg.





Amount of Emissions Saved (2030-2050) and Cost Effectiveness

Taking into account all the factors discussed above, certain which will increase the emissions:

- Penetration of AC
- Transition to BEV requiring larger charge sizes
- Shift in purchase of high quality RRR machines with high recovery rates to lower quality machines with low recovery rates
- Better refrigerant reporting and traceability, which could improve the quality of the data reported and could result in higher reported emissions or a narrowing of the bracket between the low case and the high case

And certain factors which reduce emissions:

- Accident prevention measures

The base case emissions are estimated between 2030 and 2050 to be between 607,058kg and 1,799,924kg

Implementing the suggested legislative measures to reduce emissions and increase transparency:

- RRR machine standards
- Better refrigerant reporting and traceability
- ATF audits

The total emissions between 2030 and 2050 are estimated to reduce to between 279,937kg and 816,301kg, representing emissions savings of between 327,121kg and 983,614kg or a reduction in emissions in the period between 54% and 55%

2030-2050	Low case	High case
Total emissions Base Case (kg)	607,058	1,799,924
Total emissions RRR machine standards and accident reduction measures (kg)	279,937	816,301
Saved emissions (kg)	327,121	983,614
Total emission reduction 2030 to 2050	54%	55%
Cost of reduction (EUR/kg)	26.27 EUR/kg	8.74 EUR/kg

Refrigerant reclamation

Workstream Description, Data Set Used, Refrigerant Emissions

The refrigerant reclamation entails the operations to transfer the recovered refrigerant from cylinders into bulk tanks, transferring the refrigerant to a cleaning facility (or distillation column), sampling for quality control and transfer to bulk storage. During these operations, very small quantities of refrigerant are emitted to the environment. The current technology already greatly limits the amount of refrigerant emitted allowing the different value chain players (producers OEMs and down packers) to meet their emission permitting requirements and to reduce the loss of valuable refrigerant. Pipe vacuum operation, automatic filling stations, and the use of ultra-low emission valves allow the emissions to reach a very low level. Discussions with distributors and producers showed this is common industry practice. It is estimated that the emissions during recycling will not represent more than 0.01% of the total recycled/reclaimed refrigerant. This has been calculated based on the expected recovered refrigerant estimates as part of the end-of-life workstream.

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