ENGINEERING TOMORROW

Danfoss

Refrigerant options **now** and in the **future**

A white paper on the global trends within refrigerants in air conditioning and refrigeration seen from a Danfoss perspective. Updated April 2024.

www.refrigerants.danfoss.com

Policy Statement

Danfoss encourages the sustainable development and use of low-GWP refrigerants to minimize global warming while helping to ensure the continued green transition of energy systems and food chains from production to market along with the future viability of our industry.

We will enable our customers to achieve these refrigerant goals while continuing to enhance the energy efficiency of refrigeration and air-conditioning equipment.

Danfoss will proactively develop products for low-GWP refrigerants,
both natural and synthetic,
to fulfill customers' needs for practical and safe solutions without compromising energy efficiency.

Danfoss will lead and be recognized in the development of natural refrigerant solutions where ever possible.

Danfoss will develop and support products for
low-GWP synthetic refrigerants, particularly for those applications where natural refrigerant solutions are not yet practical or economically feasible.

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Executive Summary

Danfoss, a world leader in the supply of compressors and controls, has one of the most extensive and complete product ranges in the HVAC/R industry. Our products are found in numerous business areas, such as food retail, commercial and industrial refrigeration, air conditioning, products for wholesale refrigeration, and automation in various specific industrial sectors. More than 90 years of experience has put Danfoss at the forefront in developing products using refrigerants and in evaluating the viability of new refrigerants as they are introduced. This paper contains a summarized look at our experience and knowledge, describing the background, trends, and drivers that frame the scenarios for present and future refrigerant selection.

The history of refrigerants is long and cyclical. We predict that vapor- compression systems will remain the primary and most cost efficient technology for the foreseeable future and anticipate that refrigerant consumption will increase dramatically with the growing demand from the green energy transition and emerging economies. Pairing systems and technologies with the most suitable refrigerants is a decision that will impact users for years to come. Most experts point to safety, affordability, and environmental friendliness as the most important factors to consider when building a system. But a balance of these factors can't be found in just one refrigerant for all applications.

Selecting new alternatives implies investments, costs, and educational burdens, but we believe that if these selections are made correctly, and with an innovative approach, they can open doors to new opportunities. By developing new safe technologies and procedures for handling systems, we know that we will continue to move towards much lower GWP refrigerants than are currently in use today. We foresee a decade of intensive product and system development as well as a challenging market adaptation which will be dependent on the specific regions and emerging societal needs. However, the global agreement on an orderly phase-down of high- GWP refrigerants will ensure that we are heading in the right direction.

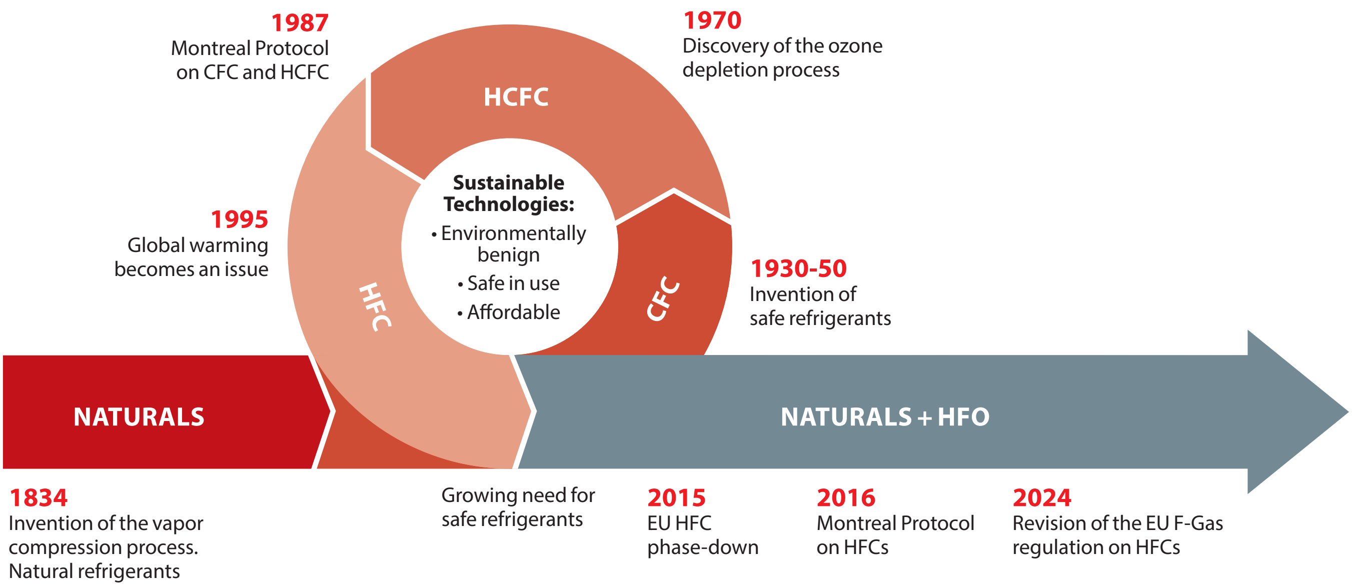


Figure 1: The historical cycle of refrigerants.
More info about the history in Appendix 3.

Refrigerant Regulations

Regulations, both national and international, have been some of the most important drivers for spurring investment in new technology. Figure 2 charts an overview of the main HFC phase-downs that have already been imposed on the industry. Be aware the EU F-gas revision has been published and the new phase down targets are changed compared to previous version of the white paper. The measures for reducing HFC consumption are mostly forced by regulation, and they all mean to place limits for consumption within the market. Specific guidance measures on market development—like GWP limits for certain applications—generate often challenges for market readiness and applicable safety standards. When new regulations are made, they are intended to encompass and balance the guidance measures and industry concerns. This is illustrated in figure 3.

HCFCs—particularly R22—are already phased out in all non-developing countries. Developing countries began phasing out HCFCs in 2015 and will continue until 2030. It is important to notice that the HCFC R22 can be used in many different applications, which makes the phase-out a challenge as no single non-flammable low-GWP refrigerant can replace it. Appendix 1, table 2 shows the HCFC phase-down steps.

In October 2016, the global HFC phase-down steps were agreed and became part of the Montreal Protocol, also called the Kigali Amendment—which came into force on January 1, 2019. If ratified by a country after that date, the Kigali Amendment will enter into effect in the country 90 days afterwards (see Appendix 1, Table 2 for the HFC phase-down steps). There is a special activity aimed at improving energy efficiency while phasing down HFCs called the Kigali Cooling Efficiency Program (KCEP). The KCEP is spurring the introduction of sustainable technologies in the fast-growing cooling segment.

Besides the phase-down and phase-out mechanisms discussed above, many governments are applying measures for reducing high-GWP refrigerant consumption, such as GWP-weighted taxes. To date, Spain, Denmark, Norway, and Sweden have imposed taxes on HFCs. Additionally, national incentives in the form of subsidies on low-GWP refrigerants are currently being used in e.g Germany.

In Appendix 1, a detailed overview is made for the main regulations including the Montreal Protocol, the EU F-gas regulation, and the US SNAP regulation including the California HFC rules.

HFC consumption phase-down for art. 5 and non-art. 5 countries

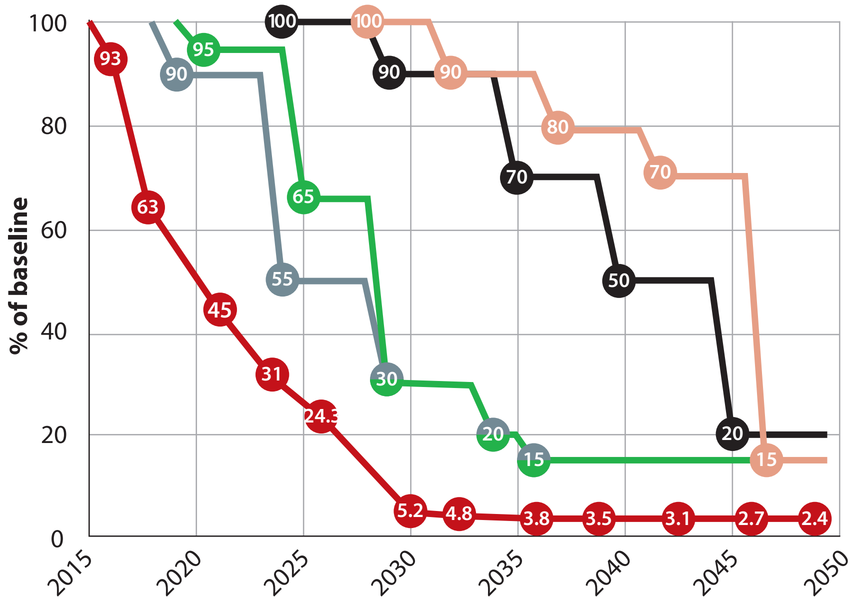


Figure 2: Refrigerant phase-down (MP and EU). See more details in Appendix 1.

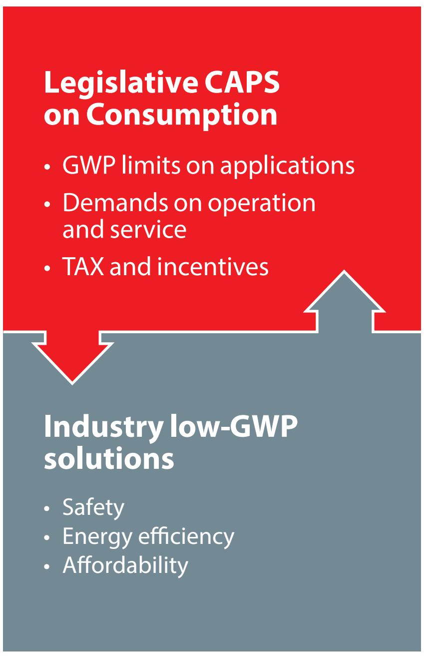


Figure 3: Dynamic between the legislative frame and the industry solutions.

Europe: Potential Restrictions on PFAS

In February 2023, Germany, the Netherlands, Norway, Sweden and Denmarksubmitted a joint REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) proposal restricting the use of PFAS. PFAS—Per- and Polyfluoroalkyl substances—are a complex group of more than 12,000 chemicals that have been linked to environmental contamination and negative health effects in humans e.g. fire fighting foams based on PFAS substances have been reported as the source for several severe cases with direct exposure to the environment. The majority of F-gases falls under the definition of PFAS as well as their potential breakdown product called TFA (Trifluoroacetic acid). Be aware that not all F-gases are PFAS-classified as they do not contain a CF3 part. Some of the PFAS-classified HFOs have very small TFA yields from breakdown, while others have 100 % TFA formation. The degree of TFA breakdown depends on the chemical composition of the refrigerant and is highly complex and involves various atmospheric parameters. Simple molecules like R32 will not form TFA while R1234yf is known to degrade 100 % to TFA. With consistent press coverage and debate around PFAS, applying a scientific and evidence-based approach is critical to evaluating the topic. The recent published report [Environmental Effects of Stratospheric Ozone Depletion, UV Radiation, and Interactions with Climate Change ; UNEP 2022 Assessment Report of the Environmental Effects Assessment Panel], states that refrigerants caused TFA concentrations are of low concern. TFA is ongoing being evaluated for its biological influence.

HFCs are effectively being phased down under the F-gas regulation while HFO's in principle can be replacement options for high GWP HFCs. Several high consuming applications are tageretted to have full F-gas ban in 2032 and 2035 and that will reduce emissions considerably, Besides the full bans, there are several mechanisms in the F-gas regulation that will target recovery, recycling and reclaim of refrigerants. The aim is to be able to reduce emissions from whatever refrigerant is used. This will also be a major factor for robust energy efficiency through system lifetime. To have a double regulation on F-gases will be very difficult to handle and should be avoided.

The proposed PFAS restriction is still in the evaluation process. Danfoss follows the process and the new scientific investigations. The topic is extremely complex seen from a physical and chemical perspective and thorough analysis needs to be done. In figure 4 a outline of the main dates are seen. During 2023 it became clear that the evaluation process is heavily delayed due to the complexity of the subject and the huge amount of responses during the consultation period. Entry into force is now projected to be within the timeframe of 2027 to 2028 .

REACH Restriction on PFAS: Process Schedule

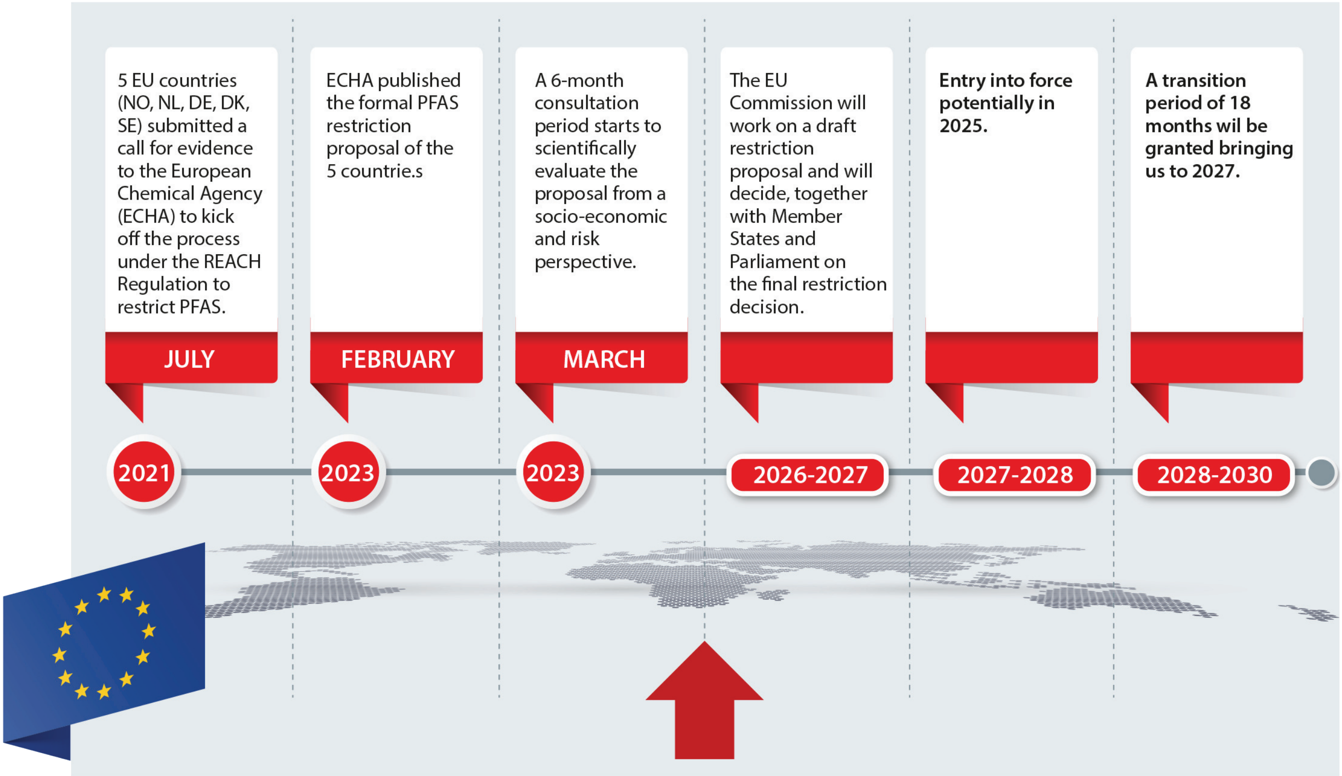


Figure 4: Process schedule.

Standardization and Risk Assessment

All refrigerants are safe in usage if safety standards and safe-handling guidelines are followed. Standards ensure common practices, technological alignment, and legal conformity. This last point being important from the industry's point of view since it reduces risk and provides legal assurance when new products are developed and applied correctly by our customers. Danfoss contributres in the standardization work behind the development of important safety standards such as ISO 5149, EN378, and ASHRAE 15.

In Figure 5 a global overview of the main safety standards can be seen. The development of standards is moving towards a wider acceptance of flammable refrigerants. The color coding towards 'red' shows the trend towards more enclosure of flammable refrigerants.

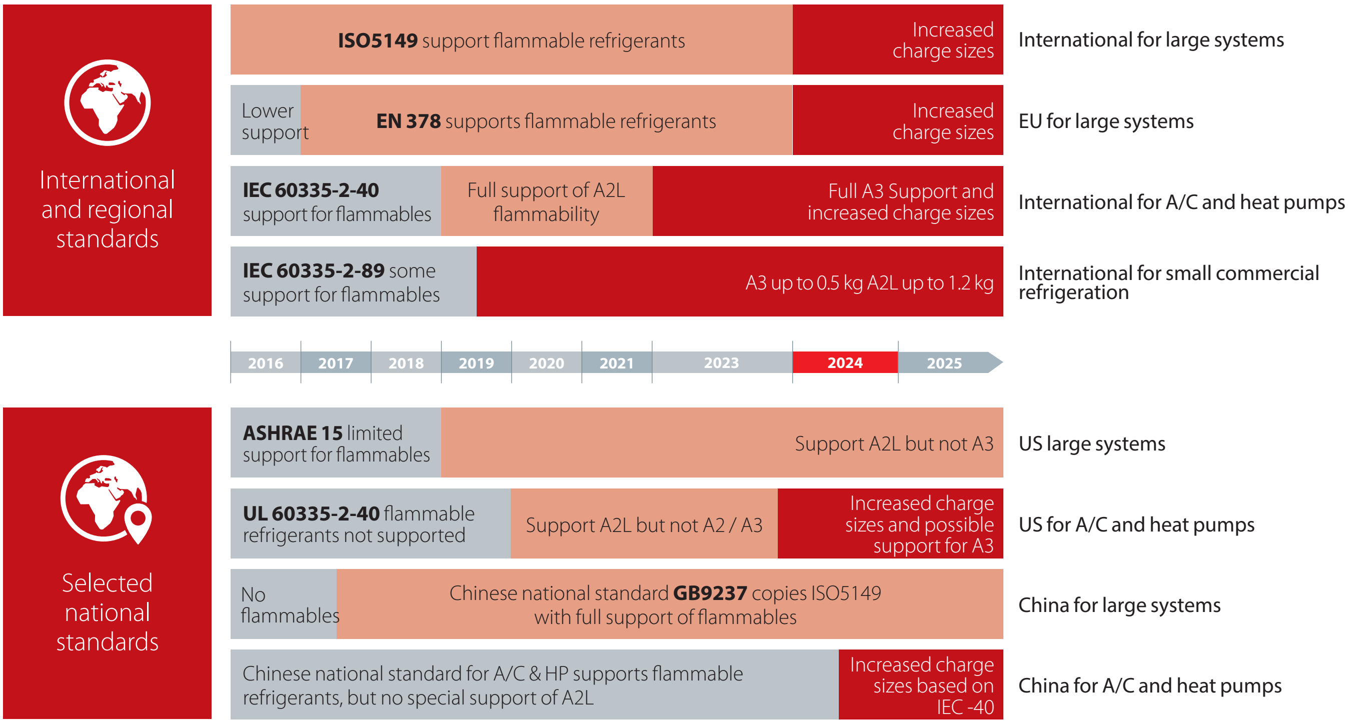


Figure 5: Safety standards development - recognising the need for flammable refrigerants.

Figure 6 shows how refrigerant standards are connected to safety standards. For example, ASHRAE 34 was used in ISO 817 to create the refrigeration classifications. These classifications are in turn used in safety standards like ISO 5149, ASHRAE 15, and the European safety standard EN 378. For more dedicated appliance standards the IEC standards are used and transposed to regional standards.

When evaluating refrigerants for specific applications, risk awareness is always a crucial parameter. Ask yourself, "What level of risk is acceptable?" Before answering, keep in mind the difference between perceived and actual risk. Perceived risk of the new refrigerant tends to be seen as higher than the actual risk. As industry competence and user experience increase, we will see a reduction in the perceived risk of using a new type refrigerant. Compare this to the perceived risk of flying versus driving a car: driving a car is often perceived as being safer than air travel, while the opposite is true. It is important to notice that all system builders must make a risk assessment of their systems during use and service.

The development of standards is moving towards a wider acceptance of flammable refrigerants. Figure 7 presents an overview of the development of the main standards and the inclusion of flammable refrigerants.

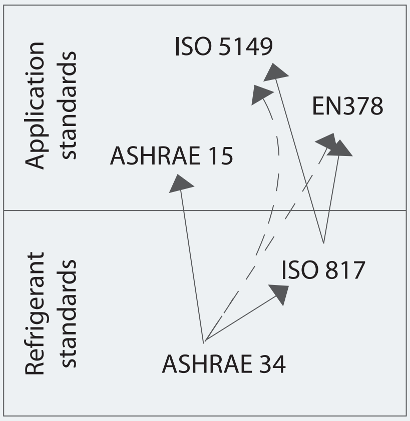


Figure 6: Refrigeration and application standards.

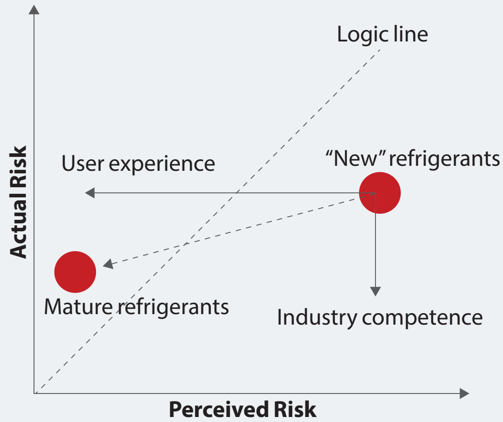


Figure 7: Perceived and actual risk.

Sustainability is the Key

Regarding long-term sustainable refrigerant solutions, Danfoss considers three main parameters that must be aligned to accomplish a real sustainable balance: affordability, safety, and environmental impact .

When choosing a new refrigerant for an application, all three parameters must be considered together to achieve long-term, sustainable results. It is important to look at the many underlying parameters such as lowest life-cycle cost, service availability, operational efficiency, safety, and the GWP of the refrigerant. A sustainable solution will be achieved only when all of these parameters are balanced. Achieving this balance will require a thorough evaluation of the factors which influence these parameters as shown in Figure 8.

Long-term sustainable solutions may not necessarily be economically viable in the short term. While we can engineer a sustainable solution, there are more factors that will determine whether new refrigerant solutions are viable. To quantify the industrial viability of developing new sustainable solutions for new refrigerants, Danfoss has developed a model that breaks down the main parameters.

We call this the Seven Forces model. The red arrows refer to economic factors and the grey arrows are cultural factors such as knowledge, education, and legislation. When the balance between the red and grey forces reaches the viability level, it becomes much more likely that the industry will start investing in new solutions and technologies. When investing in new technologies and building up competencies, legislation and derived standardization are the major drivers.

Over the past ten years, the viability level has been increasing for many low-GWP refrigerants. Good examples are CO_2 applications for commercial refrigeration, especially supermarkets.

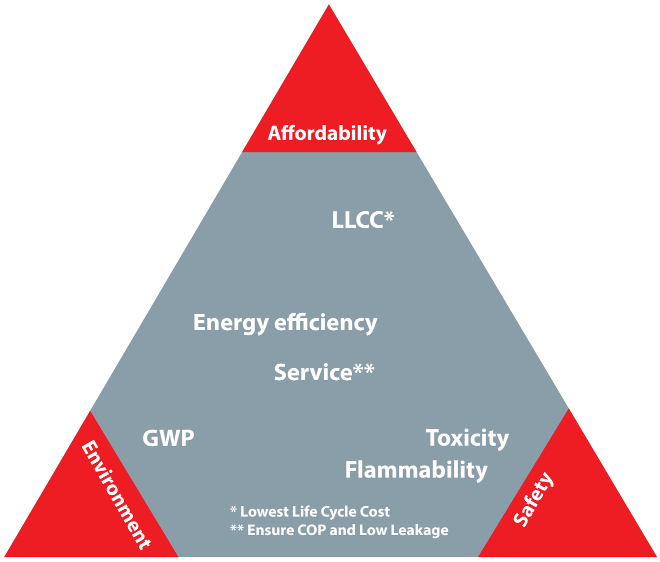
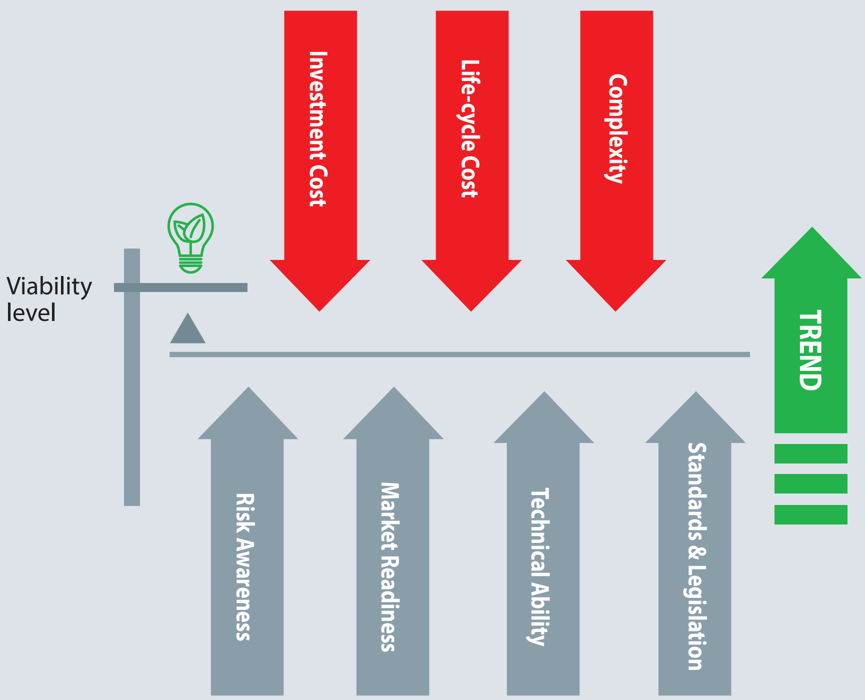


Figure 8: Refrigerant sustainability triangle



1. Investment cost
Investments in product development

2. Life-cycle cost
Life-cycle cost for the consumer. Contains upfront cost and running cost

3. Complexity
Complexity associated with manufacturing and operating the product

4. Risk Awareness
Difference between perceived and actual risk of using the product

5. Market Readiness
Market competence in safe adoption of new technologies and products

6. Technical Ability
Ability and competence in developing new products

7. Standards & Legislation
S&L includes bans, taxes and voluntary agreements

Figure 9: The Seven Forces model

The Outlook

The sustainability triangle (Figure 8) shows the three sustainability parameters and their diverse facets. Both system manufacturers and users want long-term solutions that are environmentally benign, safe, and affordable. Natural refrigerants have a ultra low-GWP and they are efficient. We expect them to become the preferred choice whenever possible; though safety will still be a limiting factor for some applications.

The trend shows a growing acceptance of mildly flammable, A2L refrigerants, especially now that they have been incorporated into the new ISO and IEC standards allowing for charge sizes that are appropriate for substitution of the high GWP HFC's. We also see highly flammable, A3 refrigerants increasingly being used though in smaller systems: A3 refrigerants are also supported by the new IEC 60335-2-89 standard which allows for up to 500 g of A3 refrigerant in hermetical systems. To allow for higher cooling capacities increased charge sizes are necessary. A new measure is to consider 'releasable charge' instead of the full system charge when evaluating the LFL (Lower Flammability Levels) . This can be justified if certain parts of the system can be isolated in case of leakage. The new measure is used in the (ed.7) IEC-60335-2-40.

Our international group of experts within Danfoss has projected what we see as the likely refrigerant outlook. This outlook is summarized in tables 1A and 1B.

CO_2 is widely used in industrial refrigeration and commercial refrigeration racks in the EU, NAM, Australia and Japan. We believe that this trend, which started in Europe, will eventually extend to the rest of the world. CO_2 heat pumps become increasingly applied up to MW sizes and often in combination with refrigeration systems using heat recovery features. CO_2 is special in the sense that often transcritical operation is utilized for the heat pump mode. This gives some advantages especially for higher temperatures but specific system conditions must be observed to ensure high efficiency compared to e.g. hydrocarbons like R290. Special attention is needed on system configuration and ejectors have shown to be a major important component.

We foresee ammonia continuing to be a very well accepted, particularly in industrial refrigeration applications, though its toxicity requires unique safety measures. Low Charge systems are available and they are very efficient. We expect that a solution using both CO_2 and ammonia in cascade will be increasingly used . We see the very energy efficient hydrocarbons playing an important role in low-charge systems around the globe and especially in the EU a big increase in air to water heat pumps for domestic usage is foreseen – however for smaller capacities. Hydrocarbons will also be increased in chillers and large scale heat pumps where the systems are placed out door or in machinery rooms. We believe that HFCs will not disappear, but will be limited to those with the lowest GWP and will be combined with HFOs as is already happening. HFC and HFO are now moving towards more environmentally friendly, but often mildly flammable, versions, making safety precautions all the more important. The potential PFAS discussion and the following uncertainties is likely to result in some regional preferences for not using F-gases. In conclusion it means a high diversity of refrigerants.

The demand for low-GWP refrigerants will continue to challenge our current perception of which refrigerants can be used in certain applications, but will also drive innovations in system design. The EU heat pump growth outlooks for the next decades will demand safe and ultra-low GWP refrigerants. This can only be obtained with natural refrigerants like R290 and HFO based solutions.

		Air Conditioning & Heat Pump																	
		Residential A/C incl. reversible systems			Rooftop units Scroll			Commercial A/C Scrolls			Commmercial A/C Screw / Centrifugal			Res. & Commercial Heat Pumps W/W			Industrial Heat pumps		
	Capacity	1-10 kW			10-30 kW			30-400 kW			400 kW - 5 MW			1-10 MW			1-10 MW		
Refrigerant	Region/Year	2024	2027	2031	2024	2027	2031	2024	2027	2031	2024	2027	2031	2024	2027	2031	2024	2027	2031
CO_2 (R744)	NAM																		
	EU																		
	China																		
	ROW																		
NH_3 (R717)	NAM																		
	EU																		
	China																		
	ROW																		
HC e.g. R290	NAM																		
	EU																		
	China																		
	ROW																		
HFC (A1)	NAM																		
	EU																		
	China																		
	ROW																		
HFC/HFO (A1 & A2L) Mid-GWP* 300-100	NAM																		
	EU																		
	China																		
	ROW																		
HFC/HFO (A1 & A2L) Low-GWP* <300	NAM																		
	EU																		
	China																		
	ROW																		

* GWP classification is somewhat dependent on current solution & operating pressure baseline.
General guidance: High > 1000, Mid 300–1000, Low < 300.

		Refrigeration														
		Domestic-Household Refrigeration			Light Commercial Refrigeration			Condensing Units			Centralised Commercial racks (Supermarkets)			Industrial Refrigeration		
	Capacity	50-300 W			0.15 - 5 kW			3-20 kW			20-500 kW			1-10 MW		
Refrigerant	Region/Year	2024	2027	2031	2024	2027	2031	2024	2027	2031	2024	2027	2031	2024	2027	2031
CO_2 (R744)	NAM															
	EU															
	China															
	ROW															
NH_3 (R717)	NAM															**
	EU															**
	China															**
	ROW															**
HC e.g. R290	NAM															
	EU															
	China															
	ROW															
HFC (A1)	NAM															
	EU															
	China															
	ROW															
HFC/HFO (GWP< 150) (A2L)	NAM															
	EU															
	China															
	ROW															

** Ammonia/CO_2 cascades will dominate industrial refrigeration

Main refrigerant
Limited use and only niche applications
Regular use
Not applicable or unclear situation

*Tables 1a and 1b: Global trends in refrigeration, air conditioning and heat pumps.
Status April 2024.*

Refrigerant Options

Facing the increasing regulatory pressures to eliminate high-GWP refrigerants, many alternatives are introduced . Generally speaking there is a trade-off between GWP and flammability. As seen in Figure 10, most of the old non-flammable 'signature' refrigerants have no simple low-GWP drop-in replacements: with other words flammability is linked to GWP and refrigerant capacity. Lower GWP and higher capacity comes with increased flammability.
The main method to reduce GWP of HFCs is to make them chemically unstable (unsaturated) so they in case of release to the atmosphere will break down within a short time frame and not remain in the atmosphere. The main unsaturated F-gases , also known as HFOs (hydrofluoroolefins), are R1234yf, R1234ze (E), and R1233zd. They have very low GWP levels, are non-flammable or only mildly flammable, and belong to a group of lower density refrigerants. Pure high density HFO's as R1132 (E) are unfortunately so far to unstable to useas a single fluid refrigerant. To obtain lower GWP of higher density HFCs blends between HFOs and HFCs are made. As seen in Figures 13A and 13B, the proposed blends within the same group are similar to each other, with the main differences being based on which 'R1234 type' is used and the exact refrigerant it is replacing

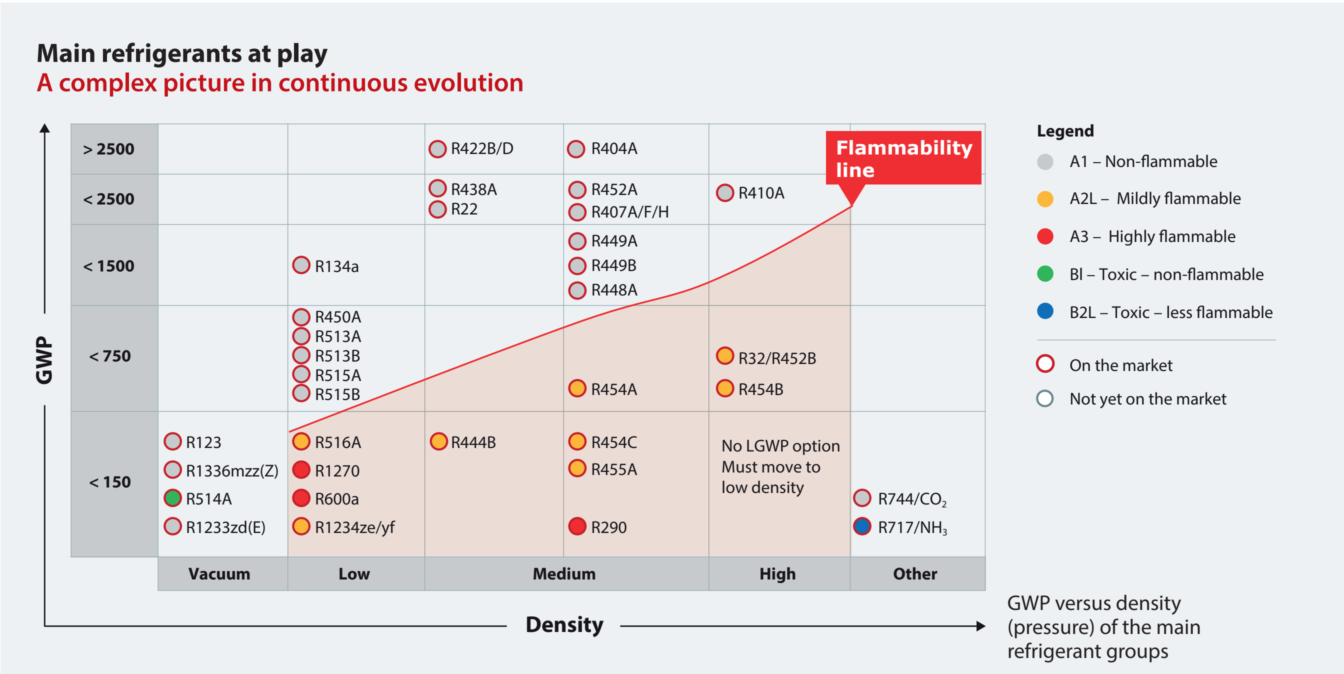


Figure 10: Carbon -chain-based Refrigerants (HCs, HFCs, HFOs, HCFCs), GWP versus density (pressure) of the main refrigerant groups.

In Figure 11 and according to ASHRAE 34, refrigerants are divided into classes depending on toxicity and flammability. A1 refrigerants are non-flammable and have very low toxicity. At the other end of the scale, with high flammability and high toxicity, no B3 refrigerants are available. Hydrocarbons, characterized by low toxicity and high flammability, require special precautions. Ammonia, on the other hand, is highly toxic and has low flammability. It is widely used, especially in industrial refrigeration due to its high energy efficiency.

The A2L subgroup is made up of refrigerants with a low flammability. Flame propagation speed is low, less than 10 cm/s. These refrigerants are already playing a significant role as we move away from the old high-GWP HFCs.

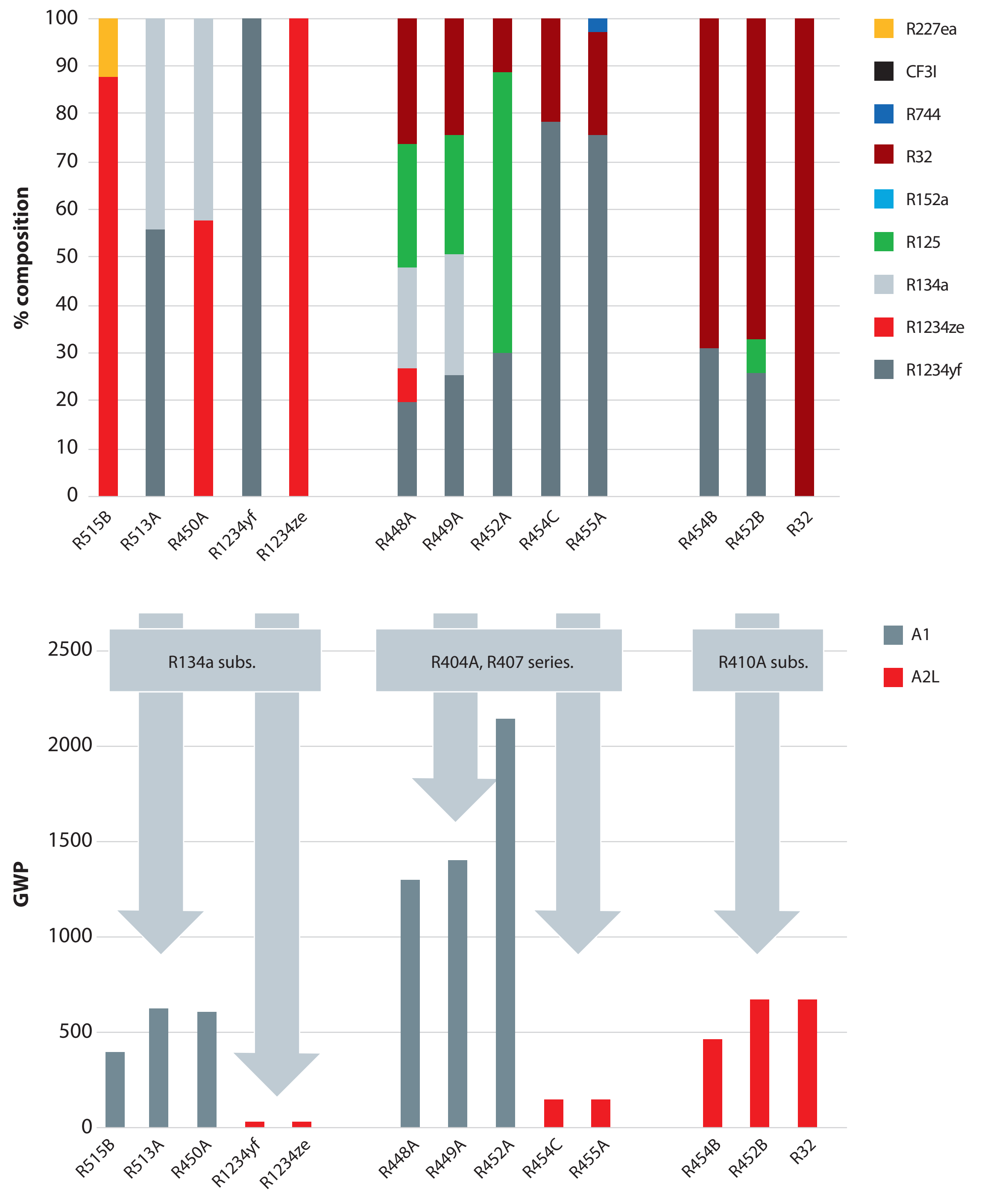
Flammability ↑ / Toxicity →	Lower Toxicity	Higher Toxicity
No flame Propagation	**A1:** CFC, HCFC, most HFCs	**B1:** Seldom used
Lower Flammability	**A2L:** Most HFOs, R32	**B2L:** Ammonia
Flammable	**A2:** R152	**B2:** Seldom used
Higher Flammability	**A3:** Hydrocarbons	**B3:** no refrigerants

Figure 11: Refrigerant classes.

There are application-specific pros and cons for using a specific refrigerant. Some important questions to ask could be : How do the energy-efficiency improvement schemes match? Is it intended for a fast drop-in or is it part of a major redesign cycle? What are the climate conditions and will the local markets be ready to handle the refrigerant? What is the impact of glide from a service an energy perspective? Will it make sense to go for one type of refrigerant or will a dual strategy be better? We recommend to make a thorough and balanced approach while using e.g. the 7 force model outlined in figure 9.

Today it is evident that A2L refrigerants are efficient and available—albeit a tremendous amount of new refrigerant releases. Components are available for the main A2L refrigerants. For R1234ze, some special conditions apply. R1234ze is categorized as an A2L refrigerant but is only flammable above 30°C. Therefore, EN 378, which is harmonized with the EU PED Directive, does not recognize R1234ze as a hazardous substance, but as a PED Group 2 fluid. This has the positive effect that it avoids material traceability for pipes and components until 32 mm in normative diameter while the other flammable refrigerants need traceability at 25 mm.

Main replacement options: composition and GWP levels



Figures 12a and 12b: The main replacement options and their composition and GWP levels.

The usage of approved components for systems containing flammable refrigerants is not a problem if the system builder is designing systems according to the safety standards. Be aware that the system builder always must perform a risk assessment and ensure that explosive atmospheres cannot arise in case of leakage.

In cases—normally accidental—where leakage occurs and where temporary flammable atmospheres are foreseen, ignition sources must be avoided or moved to a non-flammable zone. One method to avoid ignition sources is to use EX approved components. A good guideline—targeting the EU—can be found at the ASERCOM website. This guideline has been established with the input of major components manufacturers. The procedure is shown in Figure 13—note that during service, all ignition sources must be powered off.

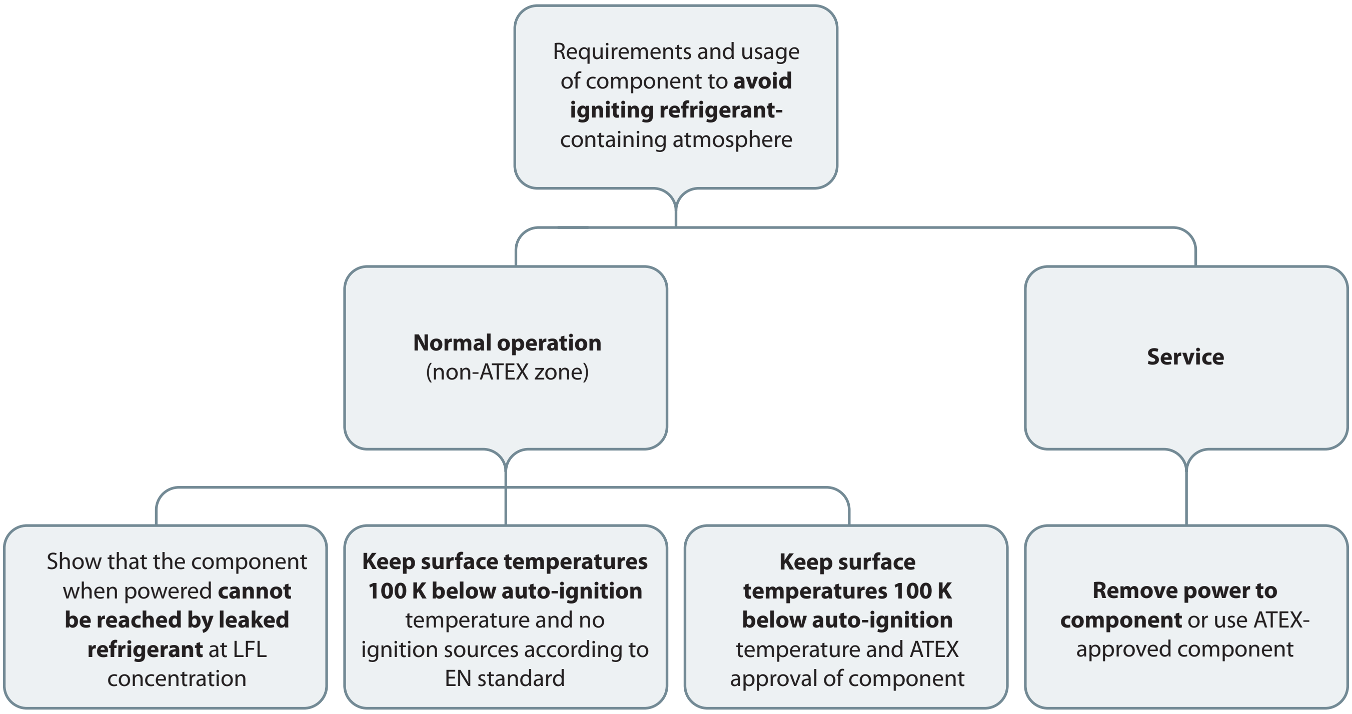


Figure 13: Requirements and usage of components in systems containing flammable refrigerants. Source : ASERCOM.

Conclusions

The vapor compression process using refrigerants are more than ever a necessity in a world where cooling and heating needs are growing. The selection of the right refrigerants has a big impact on variety of sustainability parameters. While some of yesterday's solutions have had consequences for today's environment, it is imperative that the industry looks ahead to find future-proof solutions to current challenges. Doing so effectively will require a solid working partnership with a company that not only possesses a dynamic history and a comprehensive knowledge of the current standards, legislation, and emerging technologies, but that also maintains a high focus on the future in terms of safety and environmental responsibility. Danfoss is just such a company.

With 90 years of experience, combined with our willingness to meet the challenges of today's industry, we are a leader that is poised to offer our partners sustainable solutions. Danfoss is ready to work with you in defining and implementing the best alternative for your applications. Together we can conquer today's challenges while addressing the needs of tomorrow.

Appendix 1.

Legislation and regulations

1.1 Montreal Protocol

The Montreal Protocol has two regimes to control: the ODP and GWP substances. The phase-out schedule for HCFC can be seen in Table 2 and the phase-down schedules for HFC can be seen in Table 3. It is worth noting that the non-A5 countries rely on baselines that are frozen already while the A5 countries have a combination of the HCFC quota (already frozen) and a HFC consumption, which has yet to come.

This uncertainty regarding the baseline has triggered some speculation about the missing incentive for A5 counties to have an early move to low-GWP refrigerants as this would decrease their baseline. Reality seems however to be that lower GWP refrigerants are introduced in the A5 countries with high speed.

Group I: HCFCs (consumption)

Non-Article 5(1) Parties: Consumption (Developed Countries)		Article 5(1) Parties: Consumption (Developing Countries)	
Base level:	1989 HCFC consumption + 2.8 per cent of 1989 CFC consumption	Base level:	Average 2009 – 2010
Freeze:	1996	Freeze:	January 1, 2013
35% reduction	January 1, 2004	10% reduction	January 1, 2015
75% reduction	January 1, 2010	35% reduction	January 1, 2020
90% reduction	January 1, 2015	67.5% reduction	January 1, 2025
100% reduction	January 1, 2020, Allowance of 0.5% of base level consumption until January 1, 2030 for servicing of refrigeration and air- conditioning equipment existing on 1 January 2020.	100% reduction	January 1, 2030, Allowance of 2.5% of base level consumption when averaged over ten years 2030 – 2040 until January 1, 2040 for servicing of refrigeration and air-conditioning equipment existing on 1 January 2030.

Table 2: HCFC phase-out schedule and baselines
Source: UNEP

	Non A5-1	Non A5-2	A5-1	A5-2
Freeze	–	–	2024 (100%)	2028 (100%)
Step 1	2019 – 90%	2020 –95%	2029 – 90%	2032 – 90%
Step 2	2024 – 60%	2025 – 65%	2035 – 70%	2037 – 80%
Step 3	2029 – 30%	2029 – 30%	2040 – 50%	2042 – 70%
Step 4	2034 – 20%	2034 –20%	–	–
Final	2036 –15%	2036 –15%	2045 – 20%	2047 – 15%
Countries	All non A5 except non A5-2 and the EU	Belarus, Russia, Kazakhstan, Tajikistan, Uzbekistan	All A5 expect A5-2	India, Pakistan, Iran, Iraq, Bahrain, Kuwait, Oman, Qatar, Saudi, Arabia, UAE
Baseline	HFC-average (2011 – 2013) + 15% of HCFC baseline (non-A5)	HFC-average (2011 – 2013) + 25% of HCFC baseline (non-A5)	HFC-average (2020 – 2022) + 65% of HCFC baseline (A5)	HFC-average (2024 – 2026) + 65% of HCFC baseline (A5)
Comments	HCFC phase-out plan does not correspond to the 15% in 2011 - but likely reflects actual consumption	HCFC phase-out plan corresponds to the 25% in 2010 – 2014	HCFC phase-out plan corresponds to the 65% in 2020 – 2024	HCFC phase-out plan corresponds to the 65% in 2020 – 2024

Table 3: HFC phase-down schedule and baselines
Source: UNEP

1.2 MAC Directive (EU)

This directive bans the use of any refrigerant with a GWP above 150 in air-conditioning systems in motor vehicles starting from:

- January 2011 for new models of existing vehicles
- January 2017 for all new vehicles

The directive does not cover other applications.

R134a, still the most common refrigerant in MACs globally, has a GWP of 1430 and is thus affected by the ban as well. R1234yf is increasingly being introduced globally and today, several millions of cars are using this HFO in the US and the EU and China.

1.3 F-Gas Regulation (EU)

The EU F-gas regulation is considered a front runner, preceding the Kigali Amendment to the Montreal Protocol and going beyond the latter.

The first EU F-gas regulation came into force in 2006 with a focus on containment and service. In 2015 the second version came into force, introducing the phase down of high GWP hydrofluorocarbon (HFC) refrigerants. On February 20, 2024 the new EU F-gas regulation was published in the official Journal of the EU.

The latter is an extremely ambitious regulation with a long-term full phase out of F-gases. The EU and the US phase down are illustrated in Figure 14 where the 2015 F-gas regulation is shown in comparison with the new 2024 agreed phase down. From 2025 the quota is reduced significantly compared to the previous phase-down and from 2030 the available amount of F-gases even for service is challenged.

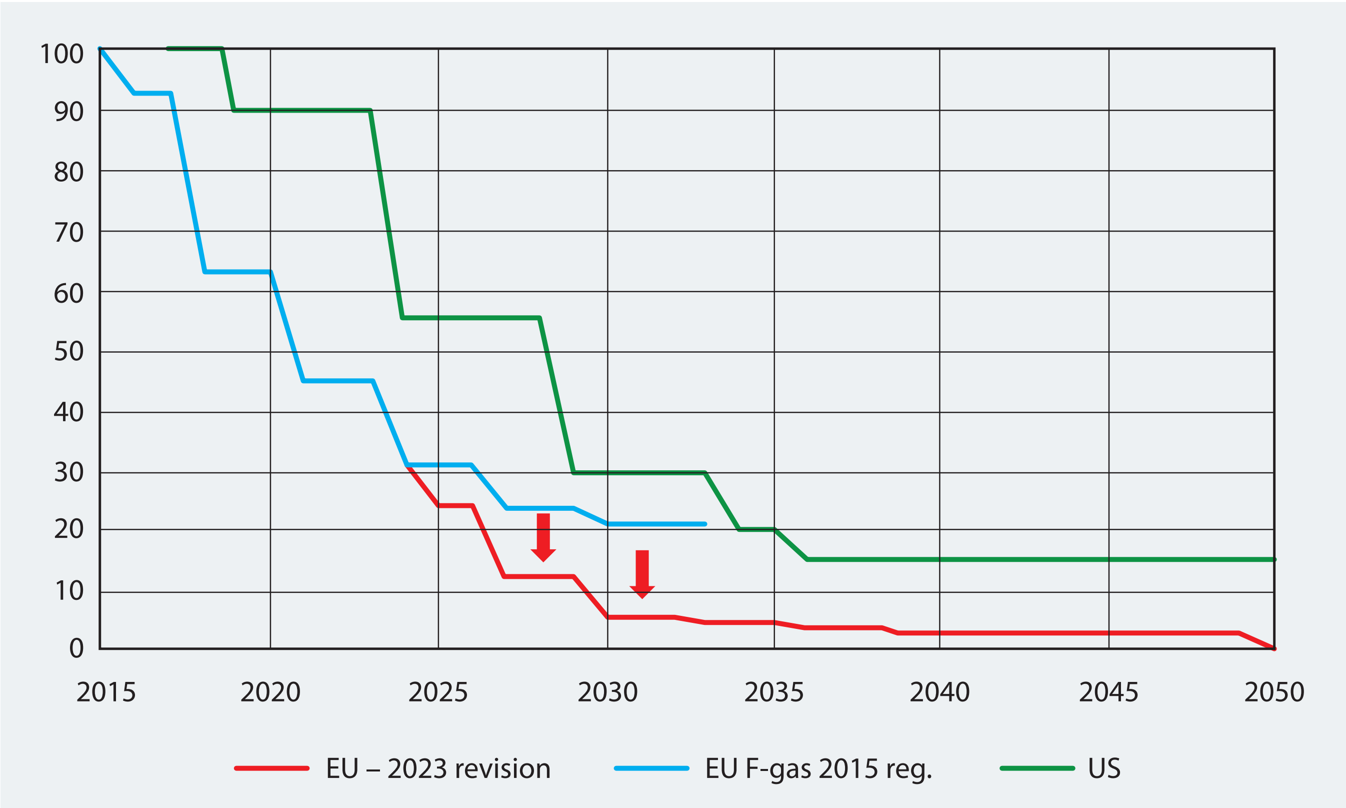


Figure 14: The phase down the EU and in the US in percentage of baseline.

The quota allocation mechanism has in principle not changed but the previously exempted Metered Dose Inhalers (MDI's) will be included in the quota as of 2025. Specific sub-quota allocations are made for MDI's and the available amount for the RACHP industry is consequently reduced with a significant percentage which still has to be exactly specified. The allocation mechanism can be found in the Annex VIII of the Regulation.

1.4 The EU equipment bans

The quota reductions are accompanied by Placing on the market Prohibitions (Bans). Compared to the last revision the amount of bans and level of detail introduced is increasing. The overview can be seen in Figure 15.

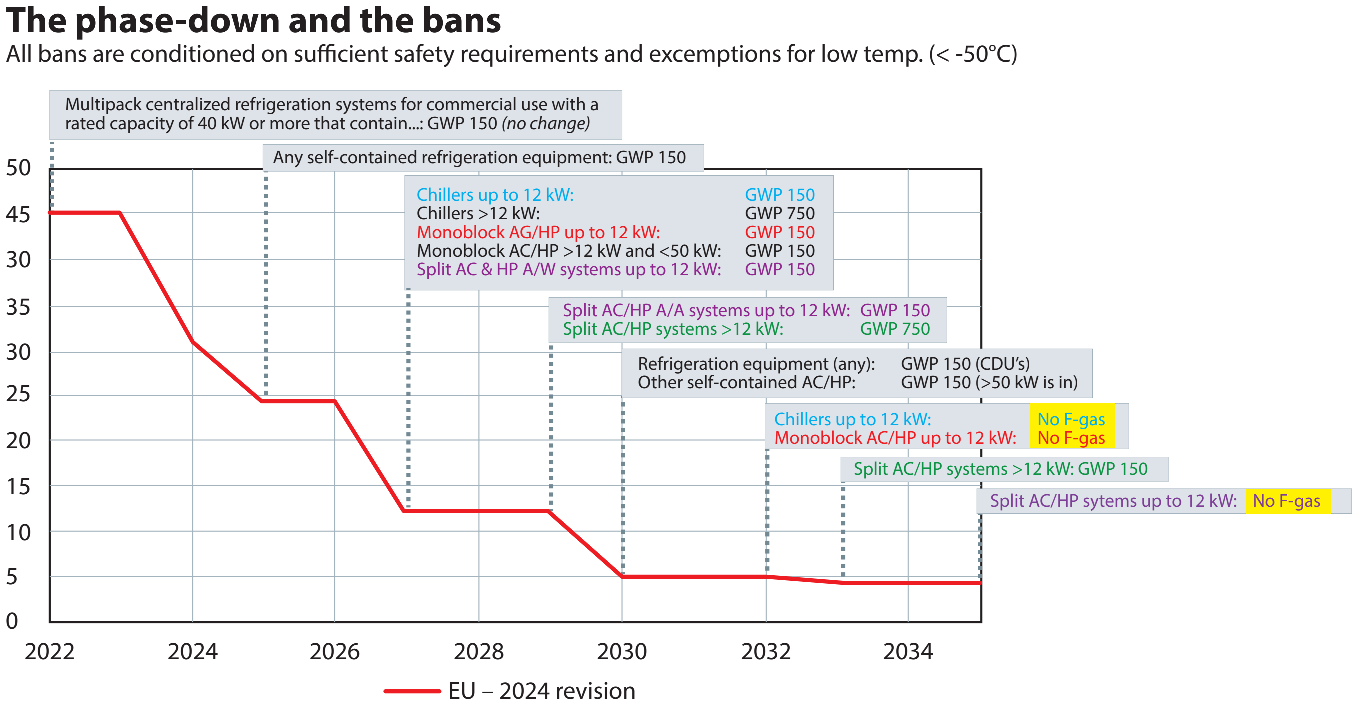


Figure 15: The Market prohibitions as in the ANNEX IV of the EU 2023 F-gas regulation.

Especially the bans outlined in Figure 15 were a big discussion theme during the review period. In the light of the aggressive quota reductions the long term consequence of having an application specific GWP ban is limited due to the pressure on availability of refrigerants via the phase-down steps (measured in CO_2-equivalents, i.e. GWP multiplied by metric quantity, resulting in highest pressure on higher GWP refrigerants) . However, it sends a clear signal to market on where to focus development efforts.

Export ban: From 2025 the F-gas regulation introduces an export ban for RACHP systems intended for the use of refrigerants with a GWP ≥ 1000 provided that these systems cannot be placed on the EU market (see Figure 15). This means that the date of the bans in Annex IV (Figure 15) will set the date for the potential export limitations. The restriction is new and there have been discussion around it. The Commission has stated that application designed for multiple refrigerant use can apply the lowest GWP refrigerant as the measure for determining whether the product can be exported. The intention of the EU is to address concerns about dumping of equipment, which is obsolete in Europe, into developing countries' markets.

Heat Pumps: The EU ambitions on decarbonizing the heating sector imply a massive rollout of heat pumps to phase-out fossil fuel-based heating. The market for heat pumps is already in acceleration mode and there have been valid concerns regarding the availability of F-gases, especially for some of the technologies. This has led to a yearly assessment and a possible extra - but very limited - quota for the years 2025-2029. The concern is particularly related to split systems <12 kW which will also be subject to a GWP limit of 150 from 2027. This can become a serious problem as raised by many industry associations. Small split systems have generally moved to the high pressure refrigerant R32 and a high pressure low GWP version is not available today. Further, the level of flammability of A3 refrigerants such as hydrocarbons, leads to liability concerns of OEMs.

On the other hand, some important applications like small (<12 kW) A/W monoblock heat pumps will have GWP limits of 150 from 2027 and a full F-gas ban from 2032. However, many of those units are today already using R290 so it is not expected to become a major problem.

Service bans: Service bans have been strengthened. As of 2025, also small refrigeration systems will no longer be allowed to use virgin refrigerant with a GWP >2500. This will target old systems still relying on R404A. From 2032 the limit will be further decreased to a GWP 750. Service and maintenance of AC and HP equipment will likewise be restricted to a GWP level of 2500 from 2026. It is important to notice that reclaimed and recycled refrigerant can still be used. An overview of the service ban can be seen in Figure 16.

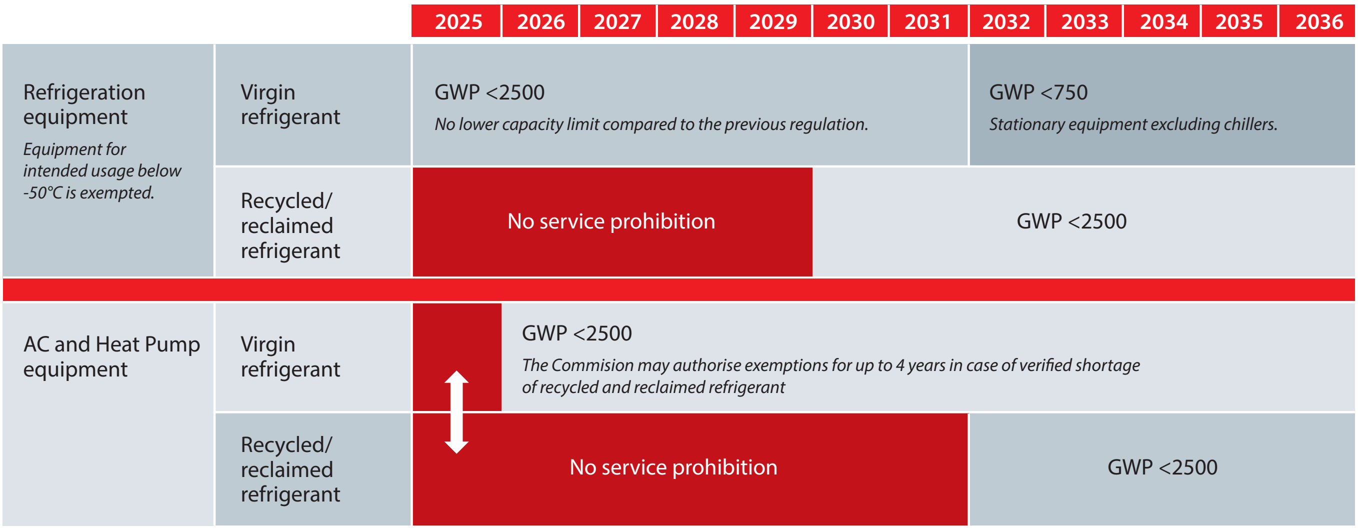


Figure 16: The Service bans imposed by the 2023 EU F-Gas regulation.

1.5 US HFC phase-down

In 2020, the US passed the AIM Act (American Innovation and Manufacturing Act) which de facto aligned already with the phase-down steps in the Kigali Amendment to the Montreal Protocol, which was ratified by the US Senate two years later, in 2022. The AIM Act provisions are now being implemented by the Environmental Protection Agency (EPA) via the Technology Transition Rule (TT). All refrigerants need to be approved via the EPA administered SNAP (Significant New Alternatives Policy) Program before they can be placed on the market and buildings codes need to allow their use. The latter have been a barrier for the deployment of flammable refrigerants – especially flammable A2L refrigerants. However, the upgrade of building codes is now well under way. The Technology Transition Rule was published in Oct 2023, listing GWP limits by sub-sector of application, some definitions are still being clarified. Compliance dates for those limits are set between 2025 and 2028 dependent on the subsector. Compared to the EU bans the implementation period of the GWP restrictions is rather short. The GWP levels are reflecting the higher US quota – compared to the EU – especially for residential AC split systems and there are no full F-gas bans long term. Figure 18 shows a simple and very limited summary overview on some main sectors. Especially in the refrigeration sector there is a considerable number of systems with a GWP limit of 150. In many of these applications we foresee the uptake of natural refrigerants like CO_2. In the higher temperature applications, the GWP limit is 700 which can be achieved with well-known A2L refrigerants like R32 and R454B.

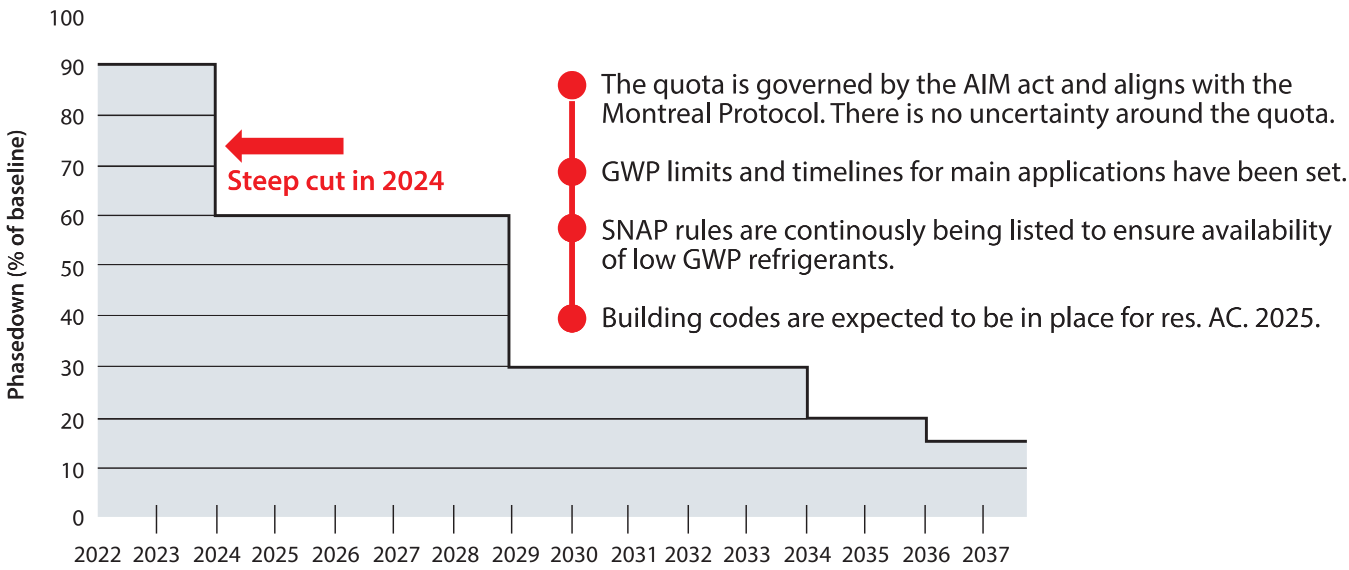


Figure 17: The US phase-down.

Following the phase down targets means that the applications will change refrigerant types dramatically. This will impact the whole HVACR value chain and likely some of the behavioral patterns observed in the EU will be repeated. The GWP limits within specific sectors can be found on the EPA homepage. Compared to the EU there is an additional approval mechanism for allowance of refrigerants. The Significant New Alternative Policy (SNAP) Program was developed by the Environmental Protection Agency (EPA) as a tool for implementation of the ODP phase-out in 1989. The SNAP concept is to accept—or eventually ban—specific refrigerants for safe usage in defined applications.

Main sectors	GWP levels	Compliance date
Refrigeration*	150-300-700**	2025-2027
Data centers	700	2027
Transport	700**	2025
Chillers	700	2025-2028
Ice rinks	700	2025
Res A/C	700	2025-2026

* Below -50°C is not covered by specific GWP limits
** See also specific listings of refrigerant for certain subsectors

- Appears more complex compared to the EU bans but likely avoids confusion on the definitions
- No full F-gas bans
- GWP limits on par with EU numbers
- Compliance dates catching up on the EU

Table 4: GWP limits for specific main sectors.

There are basically three steps in accepting and introducing a new refrigerant in the market. The first step is for the EPA to list the new refrigerant as an acceptable substitute through its SNAP rules; the second step is to establish safety standards for design and usage; and the final step is to establish building codes to accept the usage of the new refrigerant which can harmonize with safety standards. However, the three parameters are not directly aligned, and the periodic updates are not synchronized, which makes the refrigerant transition a rather lengthy process.

Given the factual phase down it is critical how the building codes will become harmonized with the ASHRAE 15 safety standard. It is of high importance that AC applications will be allowed for A2L refrigerants. California has been a frontrunner in the transition towards lower GWP refrigerants. Other states have followed and today the situation across states is nearly resolved. To take a look at the California application schedule will however give a good indication of the longer-term picture of the US especially considering the overall phase down constraint.

SNAP

SNAP Rule 17

Rule 17 allowed four specific hydrocarbons for use in household refrigerators and freezers and retail food refrigeration:

— Up to 57g R600a for the household segment
— Up to 150g R290 for the retail segment

Since this rule was established, several other applications have been allowed with an overview of additional rules forthcoming.

SNAP Rule 20 and 21

Rules 20 and 21 delist a series of high GWP refrigerants for specific applications such as chillers and refrigeration equipment. Rule 21 also accepts R290 in ice machines, water coolers, and very low temperature equipment.

Following a federal court case against the U.S. EPA, rules 20 and 21 were vacated and are now implemented according to local state legislation.

SNAP Rule 23

In 2023, the U.S. EPA issued a Proposed Rule Making for SNAP Rule 23. This rule would list several A1 and A2L refrigerants as acceptable substitutes in several sectors, including:

— Food retail: R-448A, R-449A, and R-449B
— Residential and light commercial air conditioning and heat pumps: R-452B, R-454A, R-454B, R-454C, and R-457A
— Residential and light commercial air conditioning and heat pumps excluding self-contained room air-conditioners: R-32

Rule 23 will help enable a smooth transition to A2L refrigerants.

SNAP Rule 26

In 2023, the US EPA issued a proposal for SNAP rule 26. This rule lists several HFC/HFOs and R290 for a brad range of refrigeration applications

— Commercial ice machines R32, R1234yf, R454A, R454B, R454C, R455A, R457A, R516A
— Industrial Process Refrigeration : R32, R1234yf, R1234ze(E), R454A, R454B, R454C, R455A, R457A, R516A
— Cold storage warehouse : R1234yf, R1234ze(E), R454A, R454C, R455A, R457A, R516A
— Ice Skating rings : R1234yf, R1234ze(E), R454C, R455A, R457A, R516A
— Retail Food Refrigeration – Refrigerated food processing and dispensing equipment and stand alone units: R1234yf, R1234ze€, R454C, R455A, R457A, R516A
— Retail Food Refrigeration – Refrigerated food processing and dispensing equipment : R290
— Retail Food Refrigeration – Supermaket systems and remote condensing units : R1234yf, R1234ze€, R454C, R455A, R457A, R516A
— Commercial Ice Machines (New)—Self-contained Units : R290
— Retail Food Refrigeration (New)—Stand-alone Units : R290

Rule 26 will as rule 23 help the transition towards A2L refrigerant sand also th etransiton towards R290 .

California

- California is going beyond the SNAP ruling and imposes a challenging GWP-based phase-down plan. This plan is often regarded as the trendsetter for new marketing and technology. The following targets have been set for the refrigeration sector:
- Refrigerants with a GWP greater than or equal to 150 will not be allowed in new stationary refrigeration systems charged with more than 50 pounds, effective in 2022.
- Existing food retail facilities with refrigeration systems charged with more than 50 pounds must collectively meet a 1,400 weighted average GWP or 55 percent greenhouse gas potential (GHGp) reduction relative to a 2019 baseline by 2030.
- Refrigerants with a GWP greater than or equal to 700 will not be allowed in new stationary air conditioning equipment, effective 2023.

Ice Rinks

- A GWP limit of 150 for new refrigeration systems containing more than 50 pounds of refrigerant and new chillers in new ice rinks, effective 2024.
- A GWP limit of 700 for new refrigeration systems containing more than 50 pounds of refrigerant and new chillers in existing ice rinks, effective 2024.

For air conditioning the following targets are set:

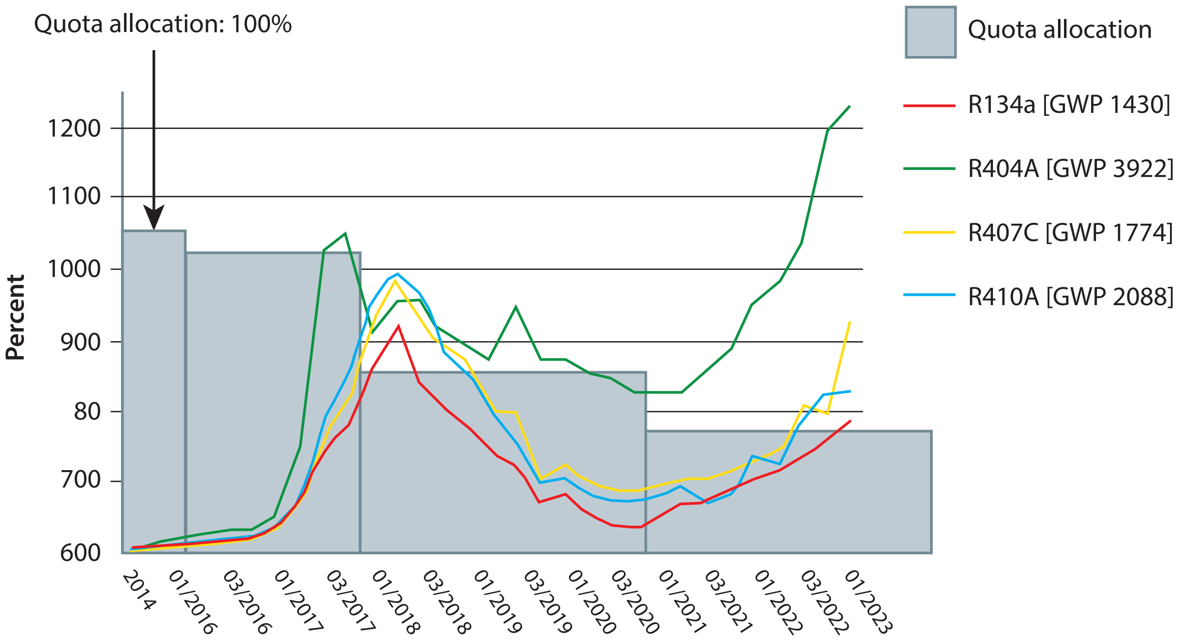
- A GWP limit of 700 for new residential and commercial stationary air conditioning equipment effective 2025 and effective 2026 for air conditioning equipment that are variable refrigerant flow or variable refrigerant volume systems.
- A requirement for a minimum use of reclaimed refrigerant in an amount equal to 10% of the amount of R-410A that enters California in new equipment in 2023 and 2024.
- A GWP limit of 700 for new chillers used for air conditioning, effective 2024.

Year	System limit for refrigerant containment in new stationary systems	GWP limit
2021	Refrigeration systems ≥ 50 pound	150
2021	Refrigeration systems ≥ 20 and ≤ 50 pound	1500
2021	Air-conditioning systems ≥ 2 pound	700
	Sales restriction on refrigerants	
2021	No production, import, sales, distribution, or entry into commerce	2500
2024		1500

Table 5: Detailed view of California's regulation on HFC restrictions.

Price development on Refrigerants

Considering the market dynamics during a phase down, some of the lessons learned in Europe may, to a certain extent, impact the speed of technology transition in the US. One very important factor is the availability of refrigerants and the timely development of the refrigerant prices. Figure 18 shows the EU price development with the overlayed quota reduction. There was obviously a delay in the price increases due to considerable stockpiling and a 'relaxed' market that didn't feel the urgency before it was too late. The market was suffering for years until the uptake of low GWP equipment started to kick in. It is difficult to predict if we will see the same trend in the US, as it depends on many other parameters such as leakage rates and the ability to recycle and reclaim refrigerants.



EU development of purchase prices at Distribution on Distributor level (Source: Öko-Recherche) overlayed with quota allocations.

Figure 18: Price development in the EU with overlaying quota reduction.

The Clean Air Act Section 608 extends the requirements for the usage of refrigerants. It lowers the leak-rate thresholds that trigger the duty to repair ACR equipment:

- Lowered from 35% to 30% for industrial process refrigeration
- Lowered from 35% to 20% for commercial refrigeration equipment
- Lowered from 15% to 10% for comfort cooling equipment

It requires quarterly/annual leak inspections for ACR equipment that has exceeded the threshold leak rate and requires owners/operators to submit reports to EPA if systems containing 50 or more pounds of refrigerant leak 125% or more of their full charge in one calendar year. It further requires technicians to keep a record of refrigerant recovered during system disposal from systems with a charge size from 5 – 50 lbs.

The AIM Act does require the EPA to set new refrigerant management rules, however, it does not dictate what those rules should be. It is expected that the EPA will begin considering its refrigerant management rules at some point in 2022.

1.6 China HCFC Phase-out Management Plan (HPMP):

The Chinese Green Cooling Action Plan submitted in June 2019 states that the HFC phase-down will follow the Montreal Protocol schemes agreed in October 2016. Besides having a focus on HFC phase-down, ambitious energy-efficiency targets for specific applications are also planned in a short period. The total picture of the HCFC phase-out and the HFC phase-down is seen in Figure 20. To fulfill the HCFC phase-out plan, the Chinese authorities are supporting projects for replacing HCFCs with alternative refrigerants according to the phase-out plan, which can be found on the UNEP homepage. Furthermore, to facilitate the HCFC phase-down plan and prepare for HFC phase-out plan, the Chinese government has requested manufacturers to declare the consumed amount of refrigerants for further quota and monitoring management.

The evaluation of candidates has not only focused on the ozone depletion potential (ODP), but also on GWP, safety and suitability for the application. The recommendations from the Chinese authorities depend on the application and the time perspective, see Table 7. The recommendations include using a variety of known low-GWP refrigerant and are backed by the adoption process of international safety standards such as ISO 5149 (GB/T9237) and the IEC 60335 series. These standards are under review and updated as the versions indicate.

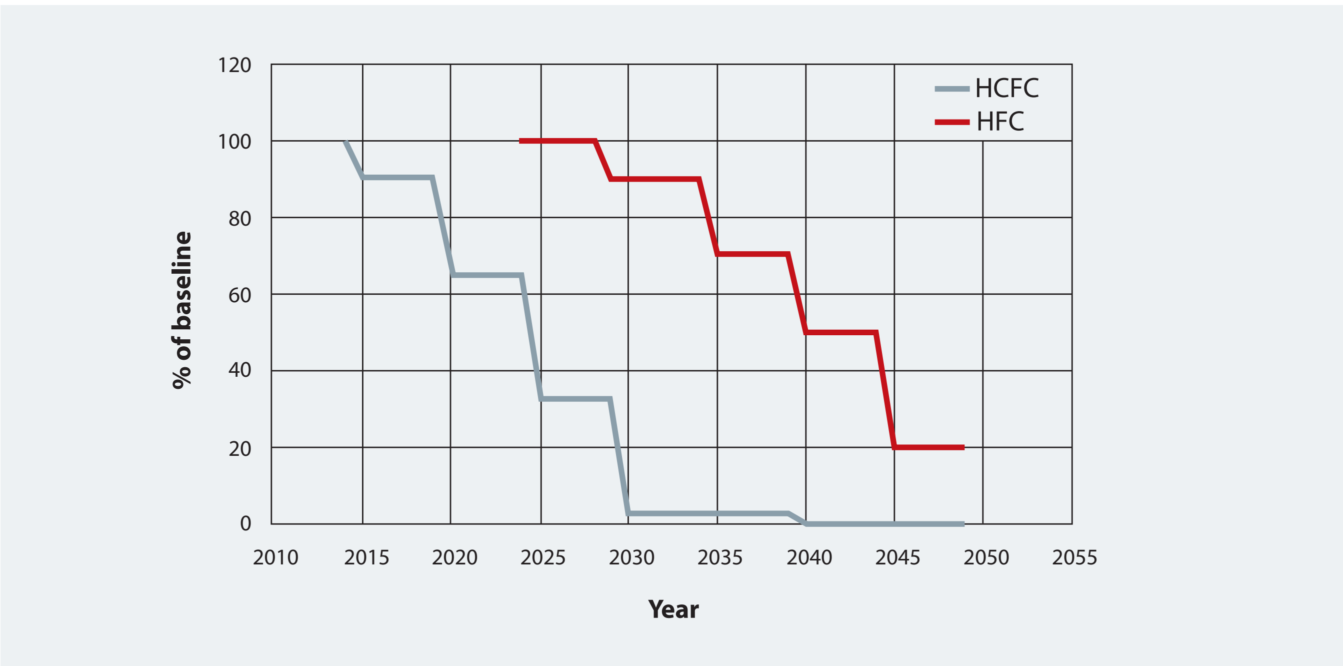


Figure 19: The HCFC phase-out and the HFC phase-down for China.

Application	Present	Mid term 2029	Long term
Centrifugal and Screw Chillers	< 1,5 MW : R134a → > 1,5 MW : R123, R134a →	R1234ze / R513A → R1233zd / R1336mzz / R514A →	R515B R1234ze
Scroll Chillers	R410A	R32	R515B
Air handling units/Rooftops	R410A	R454B	R1234ze / R1234yf / R516A
Low ambient Heat Pump	A/A: R410A → W/W: R410A →	R32 / R454C / R290 → R454C / R454B →	R454C / R290 R454C
AC Split units / VRF / CRAC	R410A	R410A / R32 / R454B	R32 / R454B
Industrial Refrigeration	R717 / R744 / R507	R717 / R744 / R507	R717 / R744
Centralised systems / Supermarkets	R22 R404A / R507	R404A / R507 R448A / R449A R744	R448A / R449A R744
Process Chillers	R22 R134a R744	R1234ze / R1233zd R744	R1234ze / R1233zd R744
Condensing Units	R22 R404A	R404A R22 R448A / R449A / R452A	R448A / R449A R452A R290
Self Contained units	R134a / R404A R600a / R290	R134a / R404A R600a / R290	R134a / R513A / R1234yf R600a / R290

Table 6: Refrigerant options per application.

China standard		IEC standard		
No	latest version	Corresponding version of IEC	No	latest version
GB4706.13	2014	2012	IEC60335-2-24	2020
GB4706.32	2012	2005	IEC60335-2-40	2018
GB4706.102	2010	2007	IEC60335-2-89	2019

Table 7: The IEC60335 series versus the Chinese standards

1.7 Japan

Japan has, in 2014, introduced a comprehensive program to reduce the emission of HFCs. The program is a life-cycle approach to reducing the GWP of the applied HFCs as well as reducing the leakage of systems in the field (service and recycling) and during end of life. The system does not apply direct bans or specific quota allocation as seen in the US or the EU. Instead it targets specific GWP values for specific applications combined with a labeling program.

Application	Target GWP value (MAX)	Target year for full implementation
Room air conditioning	750	2018
Commercial air conditioning	750	2020
Commercial refrigeration	1500	2025
Cold storage	100	2019
Mobile air conditioning	150	2023

Table 8: GWP values and timeline.

1.8 Other local initiatives

A number of countries and regions have already taken steps to promote low-GWP alternatives. Such steps include a cap on the refrigerant charge (Denmark), taxation of high-GWP refrigerants (for instance in Denmark, Norway and Australia), and subsidies for systems that use natural refrigerants (for instance in Germany and the Canadian province of Quebec).

Appendix 2.

Impact of direct leakage as a function of the leakage rate

Example:
The following example can serve to illustrate the relationship between direct and indirect impacts.

Typical refrigerant plant in a medium-sized supermarket:

- Store size: 1000 – 1500 m²
- Refrigerant: R404A
- Refrigerant charge: 250 kg
- Cooling capacity: 100 kW
- Energy consumption: 252,000 kWh/year
- Service life: 10 years
- GWP: 3920
- Operating time: 19 hours per day
- Recovery/recycling: 90%

CO_2 emissions from electricity production
Country A (fossil fuels): 0.8 kg CO_2 per kWh
Country B (hydro and wind power): 0.04 kg CO_2 per kWh

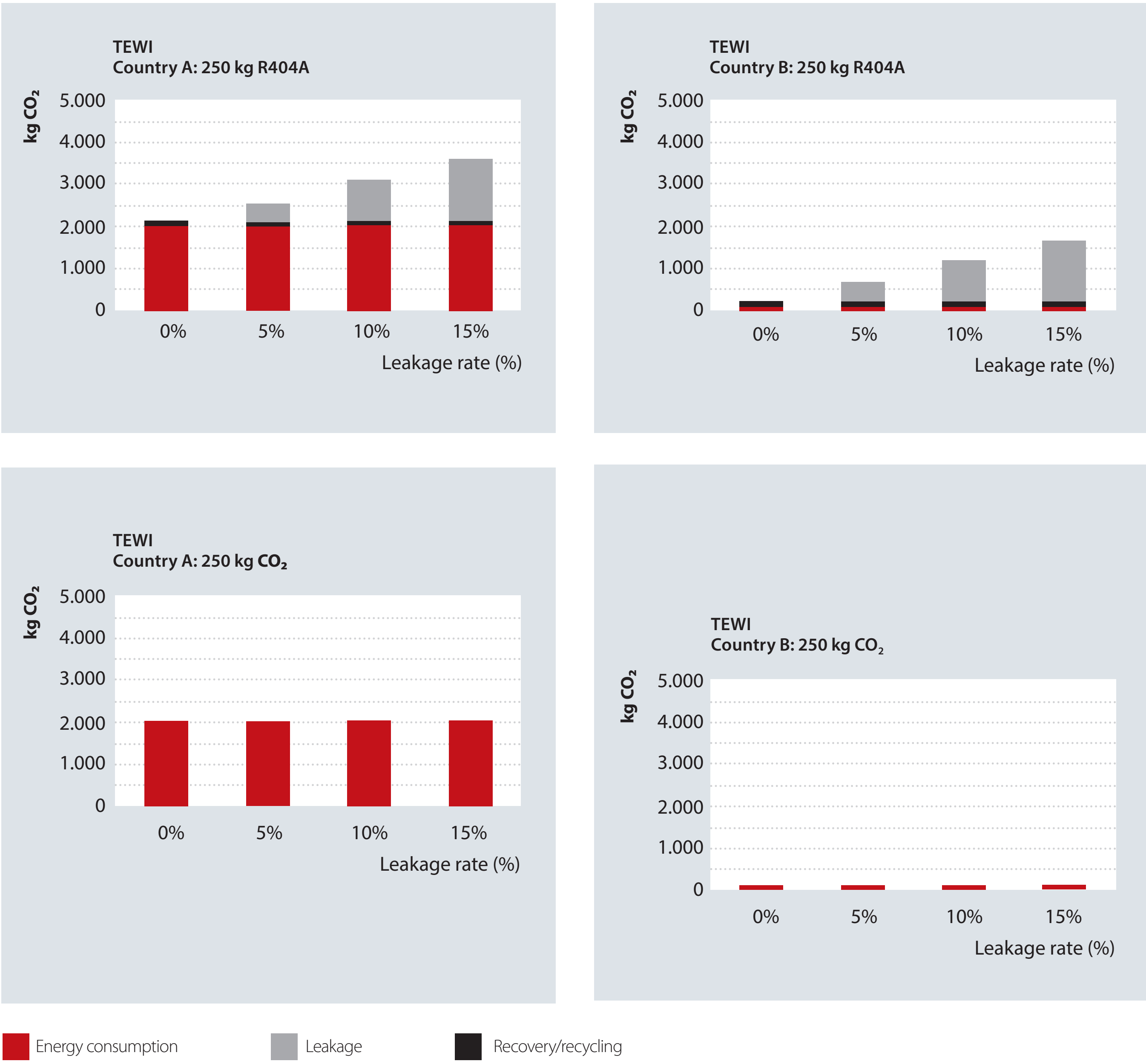


Figure 20: Relationship between the direct and indirect impacts of the refrigeration system.

Appendix 3.
History

Nearly two hundred years have passed since Jacob Perkins patented the vapor-compression cycle, which began the history of refrigerants. The vapor-compression cycle uses the refrigerant to transport heat from the cold side to the hot side of a refrigeration system, heat pump, or air-conditioning system. We use the same thermodynamic cycle today, though the refrigerants have changed.

Figure 1 shows the development of refrigerants since 1835. In the beginning, all refrigerants were easily obtainable as they existed in nature or were already used in industrial processes. By the 1930s, it became obvious that there were critical safety issues involving many of these early refrigerants, including cases of fires and poisoning caused by refrigerant leaks. It was at this time that synthetic safety refrigerants called chlorofluorocarbons (CFCs) were invented and began to be used on a global scale. Development of synthetic refrigerants continued in the 1950s, when partially chlorinated refrigerants (hydrochlorofluorocarbons or HCFCs) were introduced, including R22.

In the early 1970s, it was discovered that CFC and HCFC refrigerants caused a breakdown of the ozone layer. CFCs have a particularly high ozone depleting potential (ODP) and while HCFCs are comparatively lower in ODP, they still wreaked havoc. As a consequence, the Montreal Protocol—the global phase-down mechanism on substances that deplete the ozone layer—was established in 1987 and has since been regarded as a global success on reducing dangerous chemicals. In addition to reducing the ODP load in the atmosphere, the reduction of CFC emissions has also considerably decreased the global-warming impact. Substitute refrigerants, called hydrofluorocarbons (HFCs), have an ODP of zero, but medium to high global warming potential (GWP) though still lower than phased-out CFCs. Due to the growing threat of climate change, usage of HFCs has been scrutinized in an attempt to reduce their impact on the environment. Scientific investigations show that while the impact of HFC leaks may not currently be a major contributing factor to global warming, their growing consumption, especially within air-conditioning units in developing countries, will eventually make HFCs a top global-warming contributor if phase-down measures were not introduced. In October 2016, the parties of the Montreal Protocol agreed to a phase-down for HFCs. The phase-down came into effect in 2019 and will help significantly reduce the use of high-GWP gases.

In summary, if we do not practice environmental stewardship, refrigerants may cause severe, long-term environmental consequences. History has been a learning curve away from the flammable and toxic refrigerants towards safe solutions, but ones that were environmentally destructive, making them only short-term solutions. Technological developments, together with recognized safety standards, have finally made it possible to begin moving towards real long-term solutions with zero ODP, low GWP refrigerants.

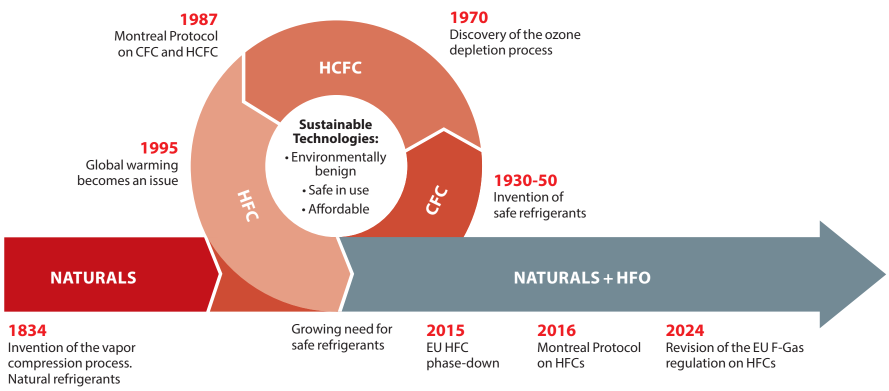


Figure 1: The historical cycle of refrigerants.

Danfoss and **low-GWP refrigerants**

Sustainable solutions are in the best interests of all stakeholders in our industry. Sustainability safeguards long-term investments and ensures compliance with Corporate Social Responsibility. Today, when talking about refrigerants and long-term sustainability, Danfoss considers three main parameters that must be aligned to accomplish a real sustainable balance: **affordability, safety, and environment.** In order to enable the market to achieve these CO_2 eq reduction targets, Danfoss is actively working on **solutions for alternative refrigerants** with a pragmatic approach, keeping system efficiency, costs and safety in mind. The company offers **a wide range of products and solutions for low-GWP** synthetic and natural refrigerants for both refrigeration and air-conditioning applications.

Refrigerant tools:

Refrigerants


Ref Tool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ENGINEERING
TOMORROW

Solutions for today and tomorrow

Intelligent solutions, combining natural, low-GWP refrigerants and high energy efficiency, are the road to sustainable refrigeration and air conditioning. Danfoss takes a proactive approach to further the development and use of low-GWP refrigerants to help abate global warming and to ensure the competitiveness of the industry.

Danfoss invests in the development of products for low-GWP refrigerants, both natural and synthetic to fulfil customers' needs for practical, safe and energy-efficient solutions. Our product portfolio already offers a full program of control components for CO_2, ammonia and hydrocarbons. The Danfoss product range is constantly developed to offer state-of-the-art energy efficiency in every component, from compressors to heat exchangers and everything in between.

Obtaining sustainable solutions is a fine balance between affordability, safety and environmental concerns. Based on our long-standing, sustainable mindset and our dedication to pioneering new technologies, we consciously pursue new developments aimed to be a sustainable balance.

Scan here for a direct access to
Danfoss portfolio for lower-GWP refrigerants

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