

Low GWP Alternative Refrigerant Selection Criteria and Performance Evaluation

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Abstract

The correct selection of refrigerants according to their application areas is a crucial matter of expertise. Today, issues such as the variety of refrigerant alternatives, their performance, environmental restrictions that vary by country, price, availability, etc. are prominent. In this context, confusion can arise among companies manufacturing in the refrigeration and air conditioning sectors. Furthermore, the purity and price of alternative refrigerants can vary depending on the technological infrastructure in the production countries. While impure refrigerants are inexpensive, they can reduce performance and damage compressors. The selection and performance evaluation of alternative refrigerants is a crucial issue, especially for companies producing in Turkey and exporting abroad. This study focuses on alternative refrigerant selection according to application areas and presents emerging long-term alternatives. The performance and application limitations of refrigerants selected according to application areas compared to existing refrigerants are theoretically evaluated. An Excel selection sheet has also been created to facilitate refrigerant selection.

Keywords: Refrigerant, Refrigerant selection, Alternative refrigerants, Performance evaluation, Environmental concerns.

Introduction

More than 80% of global Heating, Ventilation, Air Conditioning, and Refrigeration (HVACR) systems utilize fluorinated gases (F-gases), particularly hydrofluorocarbon (HFC) refrigerants. Originally adopted as substitutes for ozone-depleting substances, HFCs have an astonishing global warming potential (GWP) that is over 14,000 greater than that of carbon dioxide (CO₂).

Thanks largely to the 2016 Kigali Amendment to the Montreal Protocol, governments have aimed to phase down HFC due to their significant yet preventable greenhouse effects. While an urgent phase down of HFCs is essential for achieving climate change mitigation goals, problematic alternatives are being adopted despite the availability and ongoing development of safer options.

Currently, laws and policies aimed at reducing the use of HFCs pose a serious risk of substituting one environmental crisis with another. For example, measures that will promote the uptake of alternatives of HFC do not adequately restrict the entry to toxic and otherwise hazardous refrigerants. Of particular concern is the potential for increased pollution from per- and poly-fluoroalkyl substances (PFAS), which are already a significant public health crisis for many communities. Additionally, the production of F-gas refrigerants involves using certain carcinogens, mutagens, and reprotoxic (CMR) substances alongside HFCs. Considering the lifecycle of hydro-fluoro-olefins (HFOs), a leading alternative to

HFCs, and the ongoing presence of HFCs in HFO blends, this category of alternatives may not mitigate climate change as much as anticipated or required. Environmental justice communities are most likely to endure the adverse impacts of the F-gas production sites [1].

Energy use of refrigeration and air conditioning systems absorbed about 20% of the total electricity produced in the World and it was responsible of 7.8% of total greenhouse gas emissions in 2014, according to the International Institute of Refrigeration [2].

The life cycle of HVAC/R systems—from manufacturing to disposal—also has environmental implications. The production of HVAC/R components requires natural resources and energy, while improper disposal of old systems can lead to the release of harmful substances into the environment. This comprehensive impact makes it essential to consider not only the operational efficiency of HVAC/R systems but also their entire life cycle.

Environmental degradation and climate change are becoming more and more important problems day by day and regulations are being made for systems to work more efficiently. Due to its environmental effects, regulations regarding refrigeration and air conditioning systems are also made and updated. These rules and regulations are mostly to control the greenhouse gas emissions and ozone depleting gases on global scale. Ozone Depletion Potential (ODP) and Global Warming Potential (GWP) are defined as the main indicators to determine the effect of refrigerants on the ozone layer and global warming [3].

The Kyoto Protocol (KP) is the current overarching agreement/ treaty. It limits the emissions of a basket of 6 Global Warming (GW) gases – carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), Sulphur hexafluoride (SF₆), perfluorocarbons (PFCs) and hydro-flouro carbons (HFCs).

Refrigeration technologies can influence GW emissions in two ways. There is the direct effect due to refrigerants released into the atmosphere. Fluorocarbon refrigerants have extremely high GWPs, so small quantities can have a significant impact. For example, R134a has a GWP of 1,300 so emission of 1kg is equivalent to emission of 1.3 tons of CO₂. Also, there is an indirect effect, primarily due to energy use by the refrigeration technologies [4].

To reduce the environmental impact of the refrigeration sector globally, the World and especially the European Union have implemented different agreements and regulations that affect the refrigeration sector, such as the Kigali amendment to the Montreal Protocol [5] or the F-Gas Regulation [6].

2. Refrigerant Selection Criteria

Since mechanical vapor compression systems are very common, what will be discussed here is about the applications used in such systems. Choosing the right replacement is very easy, and the advantages and benefits of one should be primarily compared. In future it will also be necessary to assess a refrigerant's suitability for the intended application before using it.

Considering new regulations there is a need to replace refrigerants—even in existing systems—with new substances that are more environmentally friendly.

Refrigerant is the driving force behind a cooling system. As it circulates it is evaporated, compressed condensed and allowed to expand. Heat is transferred by the refrigerant evaporating at low pressure in the part to be cooled, this heat being released to the outside when the refrigerant is compressed and condensed above ambient temperature.

Choosing the right refrigerant has a significant impact on a refrigeration system's effectiveness, construction cost and energy consumption. A range of legislation and regulation need to be considered to ensure the refrigerant you select is also the best choice long-term. These guidelines will provide valuable support in selecting the right refrigerant.

But before a refrigerant can be evaluated in terms of thermodynamics and efficiency in refrigeration applications, some other aspects need a closer look: material compatibility, availability of compatible lubricants, thermal and chemical stability and general availability of the fluid in sufficient amount at acceptable cost.

2.1 Thermodynamics Properties

In heat exchangers, a two-phase mixture of gas and liquid generally achieves higher heat transfer coefficients than a single-phase gas or liquid flow at the same mass flow rate. Thus, a higher surface heat flux and consequently a lower temperature difference can be achieved. This allows for more efficient heat exchangers with relatively low material usage.

The properties of refrigerants impact the design of refrigeration equipment, which varies based on refrigerant identity, refrigeration cycle type, source-to-sink temperature difference, and the internal operative window of pressure and temperature. The key properties that are important to know for refrigerants include [7,8]:

- Critical temperature
- Critical pressure
- Saturation pressure
- Saturation temperature
- Specific volume
- Specific heat
- Thermal conductivity
- Viscosity

When selecting refrigerants, energy efficiency should be among the determining factors. Energy efficiency can be calculated theoretically for the targeted operating conditions or approximately using the performance data of the compressors with the selected compressor.

Theoretical calculations are performed using theoretical cooling capacity and isentropic compression power.

2.2 Pressure Level and Application Ranges

When considering refrigerants, refrigeration engineers first inquire about pressure levels. This essentially determines whether the components are operational and gives an idea of the cooling capacity per unit volume flow pumped, thus influencing the size of the components and piping.

Starting with the required evaporation and condensation temperature values for heat transfer flows, the corresponding values for pressure can be read from the vapor pressure curve. Vapor pressure values can also be read from the manufacturer's software for many refrigerants.

The first consideration in selecting alternative refrigerants is that the saturation curves and therefore the temperature ranges are appropriate (Figure 1).

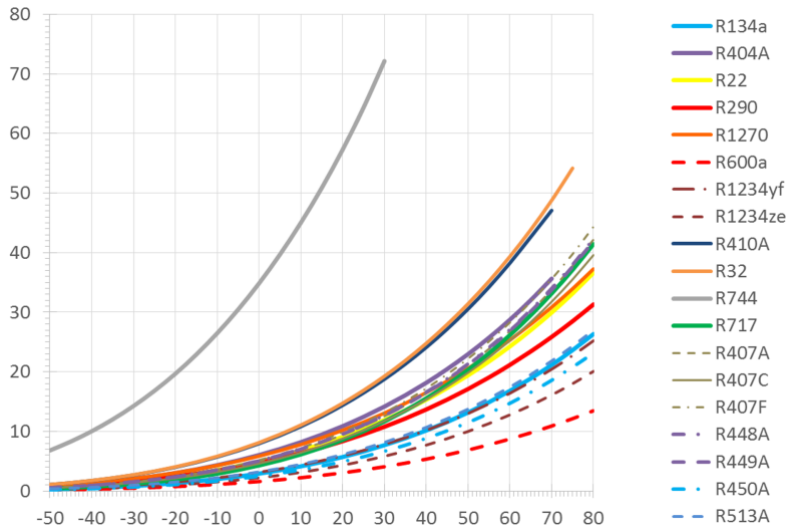
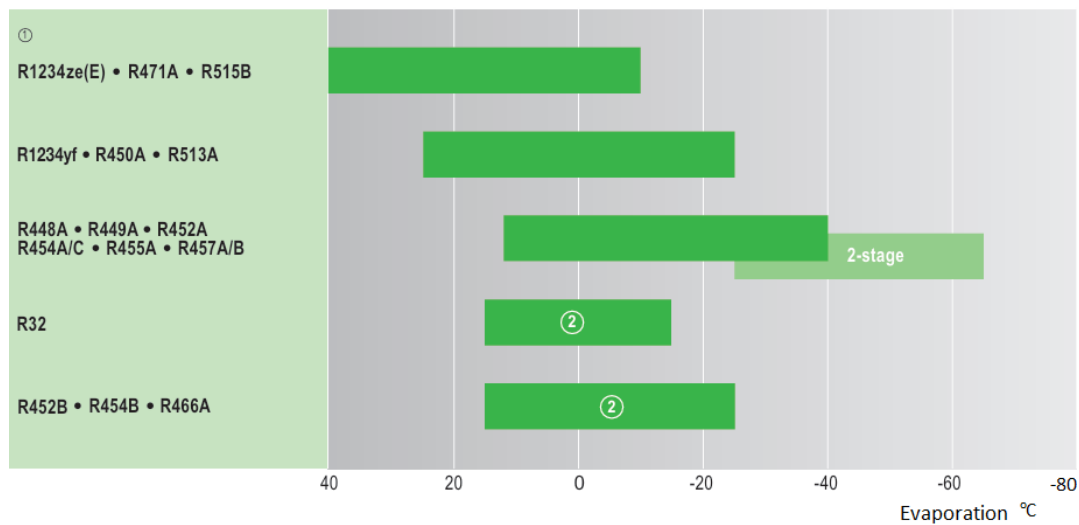


Figure 1. Vapor pressure curves, absolute pressure in bar, and temperature variation in °C for selected refrigerants.

The second important criterion in comparing alternative refrigerants is considering their evaporation temperature ranges (application ranges). Figure 2 shows the application ranges of some refrigerants with low GWP.



- (1) Figure only shows refrigerants listed in the ASHRAE nomenclature which are commercially available
- (2) Compressors for high pressure 45 bar

Figure 2. Application ranges for “low GWP” refrigerants (HFO, HFO/HFC blends, R32) [9]

2.3 Net Refrigeration Effect and Volumetric Refrigeration Capacity

Net refrigeration effect (NRE) and volumetric refrigeration capacity are frequently used in comparing the performance of refrigerants. Net refrigeration effect (NRE) is the amount of heat absorbed by each kilogram of refrigerant in the cooled area to produce useful cooling. Multiplying this by the mass flow rate gives the refrigerating capacity (RC). However, an increase in condensation pressure in the cycle reduces the NRE value, while superheating and subcooling values increase the NRE.

$$\dot{Q}_r = \dot{m}_r q_e = \dot{m}_r (h_1 - h_4)$$

Equation (1)

Where:

\dot{Q}_r : Refrigeration capacity [kW]
 \dot{m}_r : Refrigerant flowrate [kg/s]
 q_e : Net refrigeration effect [kJ/kg]
 h_1 : Refrigerant enthalpy at the evaporator outlet [kJ/kg]
 h_4 : Refrigerant enthalpy at the evaporator inlet [kJ/kg]

Volumetric refrigeration capacity (VRC) expresses how much heat is absorbed per 1 m^3 of refrigerant (kJ/m^3), considering the compressor swept volume. If the compressor swept volume (\dot{V}_{swept}) and volumetric efficiency (η_{vol}) are known, the refrigeration capacity of that compressor can be calculated.

$$\dot{Q}_r = VRC \cdot \dot{V}_{swept} \eta_{vol} \quad \text{Equation (2)}$$

Where:

VRC : Volumetric refrigeration capacity [kJ/m^3]
 \dot{V}_{swept} : Swept volume of compressor [m^3/s]
 η_{vol} : Volumetric efficiency of compressor [%]

2.4 Operating Above Critical Pressure

The COP, or efficiency, of vapor compression systems decreases as the condensation temperature approaches the critical temperature, with a constant subcooling temperature difference, as the available enthalpy difference between the dew and bubble lines decreases. In this way, the cooling capacity decreases at a constant mass flow.

Above the critical pressure, there is no two-phase space and therefore no condensation. Here, the pressure is no longer temperature-dependent but needs to be additionally controlled.

To achieve similar efficiency here, further system design or control measures are required.

2.5 Design and Performance Criteria

When comparing efficiencies, it is important to consider that different refrigerants may require different system designs for optimum efficiency at specific evaporation and condensation temperatures. Many refrigerants, such as hydrocarbons (HC) and most hydrofluorocarbons (HFCs), provide the best COP value with an integrated internal liquid-suction line heat exchanger, while this heat exchanger reduces efficiency for, for example, R717 (ammonia). Therefore, it is probably sensible to perform calculations with different operating conditions and different system designs before deciding on a refrigerant (Figure 3).

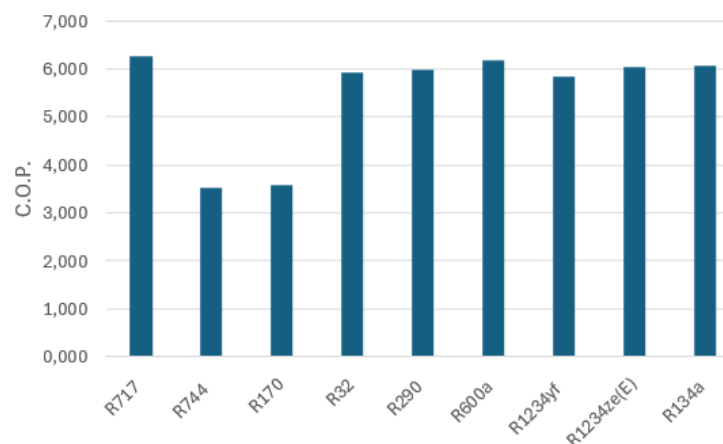


Figure 3. Standard Medium Temperature (MT) refrigeration: Evaporator -6.7°C /Condenser 30°C

2.6 Flammability and Toxicity

Two other critical considerations in today's lower GWP refrigerant selection are its flammability and toxicity. These factors pose inherent risks that must be mitigated in system design. Whether a refrigerant is flammable or toxic affects safety protocols, equipment specifications, and operational procedures. Minimizing refrigerant charge becomes imperative in such scenarios to reduce potential hazards. This challenge requires innovative design solutions that maximize internal space utilization without compromising the system's efficiency.

The requirements of ISO 817 and EN 378 standards dictate the necessity of refrigerant selection taking into account its toxicity class (A/B) and flammability (1/2L/2/3). The safest are R134a, R513A and R1234ze (A1, A2L), moderately flammable – R32, R454B (A2L), highly flammable – hydrocarbons (A3). Ammonia is distinguished as B2L: toxic but with a low propensity to combustion (Figure 4).

In practice, the choice of refrigerant today is determined by a combination of three factors: the allowable GWP, the charge volume and the location of the equipment. For systems in rooms with people (retail halls, offices), A1/A2L with limited charge is preferred; for industrial systems, NH₃ and CO₂; for small hermetically sealed systems, propane [8].

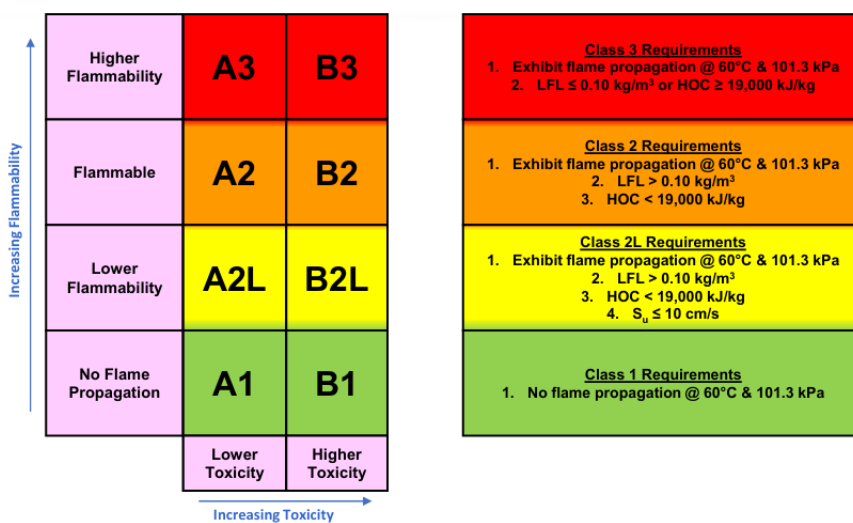


Figure 4. ASHRAE 34 classification of refrigerants [10]

2.7 Lubricants for Compressors

Positive displacement compressors-as are predominantly used in commercial and industrial refrigeration, air conditioning and heat pump systems-are commonly oil lubricated. Despite appropriate constructional measures and/or installation of an oil separator, a small amount of oil is pumped into the circuit together with the compressed gas flow. To stabilize the oil balance, suitable measures for continuous oil return must be taken. Oils that are soluble and miscible with the refrigerant are advantageous. The refrigerant dissolved in the oil significantly reduces the viscosity, improving oil fluidity and minimizing the negative influence on the heat transfer in heat exchangers.

In the past, so called naphthenic mineral oils (MO) and synthetic alkylbenzenes were preferred. For systems with CFC and HCFC refrigerants and hydrocarbons, they are very favorable regarding solubility and miscibility.

Therefore, new lubricants with appropriate solubility/miscibility have been developed for systems with HFC and HFO refrigerants. These are oil based on polyol ester (POE) and polyalkylene glycol (PAG) [9].

POE oils, although more efficient than mineral oil, are less hygroscopic and can therefore cause chemical reactions and hydrolysis. For this reason, they should not be exposed to air during servicing. PAG oils are also sensitive to moisture and are not preferred in hermetic compressors due to their low dielectric strength.

The use of polyvinyl ether (PVE) oil is becoming widespread in factory-assembled air conditioning units and water chillers. Although this oil is more hygroscopic than POE oil, it has an advantage in terms of dielectric resistance.

Ammonia (R717), used in industrial refrigeration, does not mix well with oils. Therefore, mineral oil (MO) or polyalphaolefin (PAG) oil is used, employing special oil separator systems (Figure 5).

	Traditional oils				New lubricants			
	Mineral oil (MO)	Alkyl-benzene (AB)	Mineral oil +alkyl-benzene	Poly-alpha-olefin (PAO)	Polyol ester (POE)	Polyvinyl-ether (PVE)	Poly-glycol (PAG)	Hydro cracked mineral oil
(H)CFC	Good	Good	Good	Application with limitations	Especially critical with moisture +VG			
Service blends with R22	Application with limitations	Good	Good		Especially critical with moisture +VG			
HFC + blends		Application with limitations			Good	Good	Especially critical with moisture	
HFC/HC blends	Application with limitations	Application with limitations	Application with limitations		Good	Good		
HFO+HFO/HFC blends					AD	AD		
Hydrocarbons	VG	VG	VG	VG	VG		Especially critical with moisture	
NH ₃ • R723	Good	Application with limitations	Application with limitations				Especially critical with moisture	Good
CO ₂				Application with limitations	AD		AD	

Good suitability
 Suitability dependant on system design
 Application with limitations
 Not suitable
⚠ Especially critical with moisture
VG Possible higher basic viscosity
AD Possible special formulation

Figure 5. Lubricants for compressors [9].

2.8 Phase-Down Regimes and Regulations

The selection and implementation of ecologically friendly choices heavily depend on the safety issues around refrigerants. This section examines the flammability and toxicity issues associated with refrigerants, as well as the safety requirements and installation guidelines, as well as the regulatory frameworks and phase-out timetables in place (Figure 6).

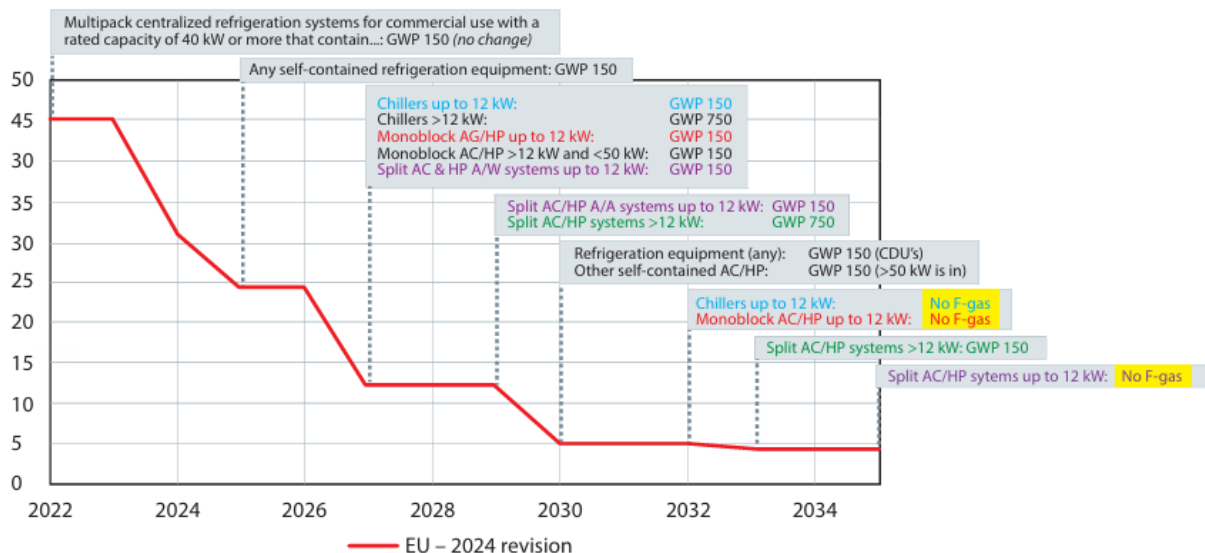


Figure 6. The market prohibitions as in the ANNEX IV of the EU 2023 F-gas regulation [7].

Regulations, both national and international, have been some of the most important drivers for spurring investment in new technology. Figure 7 an overview of the main HFC phasedowns that have already been imposed on the industry. Be aware that the EU F-gas revision has been published and the new phase-down

targets have been changed compared to previous versions of this 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—often generate 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.

EU 517 / 2014 F - GAS regulation [11]

- No bans on R134a & R410A
- Refrigerant price driven by GWP value & quotas
- Complexity & cost to import equipment in the EU from 2017

Local regulations

- Taxes in Nordic, Spain, Poland & France
- Restrictions/bans in Switzerland & Denmark

Prevent leak & emission

- Leak checks
- Recovery
- Certification of people

Reduce use of HFC's

- Phase down
- Bans (GWP> 2500 in 2020)
- Traceability

Review of the EU F-gas Regulation

The Commission is currently reviewing Regulation (EU) No 517/2014 (the 'F-gas Regulation').

This review will evaluate how well the Regulation has functioned, following the standard framework for evaluation of EU policies by examining its relevance, effectiveness, efficiency, coherence and EU added value.

The review will also analyze policy options to improve the Regulation going forward, in view of:

- the European Green Deal and European Climate Law
- recent international obligations on hydrofluorocarbons (HFCs) under the Montreal Protocol progress made and lessons learned.

This review includes a number of consultation activities, notably an open online public consultation, consultation of targeted stakeholder groups and a stakeholder workshop.

Process

The Commission launched the review in July 2020 with the publication of a roadmap, the inception impact assessment. 76 stakeholders submitted feedback on this roadmap. An open public consultation is ongoing until 29 December 2020.

EU 517 / 2014 F-GAS Regulation –Leak Checks (Table 1)

Obligation to repair leakage without undue delay (article 3.1)

Frequency of leak checks based on refrigerant charge in tons of CO₂equivalent (per circuit)

Frequency of inspections halved when a leakage detection system is installed (system must alert the operator)

Leakage detection system must be checked every year.

Table 1. Leak Checks for EU 517 / 2014 F-GAS Regulation [11]

Leakage Detection		Periodically Check			
System WITHOUT Leakage Detection		No Check	Every 12 Months	Every 6 Months	Not Allowed
System WITH Leakage Detection		No Check	Every 24 Months	Every 12 Months	Every 6 Months
Refrigerant Charge per Circuit (CO ₂ equivalent)		< 5 ton	5 ≤ Charge < 50 ton	50 ≤ Charge < 500 ton	Charge > 500 ton
Refrigerant Charge per Circuit (kg)	R134a (GWP 1430)	Charge < 3.5 kg	3.5 ≤ Charge < 34.9 kg	34.9 ≤ Charge < 349.7 kg	Charge > 349.7 kg
	R407C (GWP 1774)	Charge < 2.8 kg	2.8 ≤ Charge < 28.2 kg	28.2 ≤ Charge < 281.9 kg	Charge > 281.9 kg
	R410A (GWP 2088)	Charge < 2.4 kg	2.4 ≤ Charge < 23.9 kg	23.9 ≤ Charge < 239.5 kg	Charge > 239.5 kg
	R32 (GWP 675)	Charge < 7.4 kg	7.4 ≤ Charge < 74.1 kg	74.1 ≤ Charge < 740.7 kg	Charge > 740.7 kg
	HFO R1234ze	No Request			

EU 517 / 2022 F - GAS regulation

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Local regulations

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Reduce use of HFC's

- Phase down
- Bans (GWP> 2500 in 2024)
- Traceability

EU 517 / 2022 F-GAS Regulation –Leak Checks (Table 2)

Obligation to repair leakage without undue delay (article 4.4)

Frequency of leak checks based on refrigerant charge in tons of CO₂ equivalent (per circuit)

Frequency of inspections halved when a leakage detection system is installed (system must alert the operator)
Leakage detection system must be checked every year.

Table 2. Leak Checks for EU 517 / 2022 F-GAS Regulation [11]

Leakage Detection		Periodically Check			
System WITHOUT Leakage Detection		No Check	Every 12 Months	Every 6 Months	Not Allowed
System WITH Leakage Detection		No Check	Every 24 Months	Every 12 Months	Every 6 Months
Refrigerant Charge per Circuit (CO ₂ equivalent)		< 5 ton	5 ≤ Charge < 50 ton	50 ≤ Charge < 500 ton	Charge > 500 ton
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	R32 (GWP 675)	Charge < 7.4 kg	7.4 ≤ Charge < 74.1 kg	74.1 ≤ Charge < 740.7 kg	Charge > 740.7 kg
	HFO R1234ze	Charge < 2.0 kg	2.0 ≤ Charge < 10.0 kg	10.0 ≤ Charge < 100.0 kg	Charge > 100.0 kg

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 note that the HCFC-22 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.

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. For countries that ratified the Amendment after that date, the Amendment will enter into force 90 days after the ratification. In 2016, leading climate foundations formed the largest-ever fund for action on efficient, climate-friendly cooling.

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 for low-GWP refrigerants are currently being used in countries such as Germany [7].

The quota reductions are accompanied by placing on the market prohibitions (bans). Compared to the last revision the number of bans and level of detail introduced is increasing.

Especially the bans outlined in Figure 7 were a big discussion topic during the review period. Considering 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 CO₂-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.

2.8 Refrigerant Options

Faced with increasing regulatory pressure to eliminate high GWP refrigerants, the industry has offered many alternatives. Generally, there is a trade-off between GWP and flammability. As shown in Figure 7, most of the older non-flammable "signature" refrigerants do not have a simple low-GWP replacement alternative. Flammability is linked to GWP and refrigerant capacity. Lower GWP and higher capacity mean increased flammability.



Figure 7. Carbon -chain-based Refrigerants (HCs, HFCs, HFOs, HCFCs), GWP versus density (pressure) of the main refrigerant groups [7].

The main method of reducing GWP in HFCs is to make them chemically unstable (unsaturated) so that when released into the atmosphere, they rapidly decompose instead of remaining in the atmosphere. The main

unsaturated F-gases, also known as HFOs (hydro fluoro olefins), are R1234yf, R1234ze(E), and R1233zd. They have very low GWP levels, are non-flammable or only mildly flammable, and belong to the low-density refrigerant group. Pure high-density HFOs, such as R1132(E), are unfortunately too unstable to be used as single-fluid refrigerants. To reduce the global warming potential (GWP) of higher-density HFCs, HFOs and HFCs are mixed. As shown in Figures 13A and 13B, the proposed mixtures within the same group are similar, with the main differences being which 'R1234 type' is used and which refrigerant it replaces.

3. Material And Method

This study was prepared within the scope of the work of a working group established under the Refrigeration Industry Businessmen Association (SOSİAD). The aim of this study is to create an electronic interface for the selection and comparison of refrigerants that comply with new regulations and have low GWP. Once the study is completed, this resource information will be shared on the SOSİAD website.

The study aims to create an interface for the selection and performance comparison of low GWP refrigerants, and to perform basic calculations on this interface, including general characteristics, performance, cost, TEWI (Testicular Width of Air), and charge limit amounts for combustible refrigerants. For this purpose, an extensive literature review was conducted, and a comprehensive table including all refrigerants was created.

4. Findings And Discussion

In this study, data and/or calculation spreadsheets were created using Excel. The first of these spreadsheets covers the general properties of refrigerants. Here, the basic similarities of all known refrigerants, GWP values, ODP value, temperature drift, chemical name, chemical formula, manufacturer, which refrigerant it replaces, maximum and minimum application temperatures, maximum and minimum application temperatures in 2 stages, safety class, toxicity limits (AEL), molecular weight, boiling and dew point temperatures, critical pressure and temperature, condensation temperatures at 26 and 40 bar pressures, relative cooling capacity, temperature rise in the discharge line, and lubricant alternatives are listed.

The second of these calculation sheets shows the cost calculations for refrigerants. For this purpose, two tables have been created. One of them calculates the amount of refrigerant depending on the capacity for known refrigerants. The other is a table that calculates both the refrigerant cost, and the new equipment cost per kW of cooling capacity, depending on the application area.

The third of these calculation sheets calculates the performance (COP) of refrigerants for low, medium, and high temperature applications.

The fourth calculation sheet is designed to calculate the total equivalent heating effect (TEWI) values of refrigerants. This sheet allows you to calculate the TEWI value of commonly used refrigerants based on their application area, service life, and refrigerant quantity.

The fifth calculation sheet is an information sheet showing the toxicity and flammability classes of the refrigerants.

The final calculation sheet shows the charge limits for toxic and flammable refrigerants. Using this sheet, the minimum charge limits and required room dimensions (m²) for such refrigerants can be determined.

5. Conclusions

In conclusion, the use of environmentally friendly refrigerants is crucial for sustainable and energy-efficient refrigeration and air conditioning systems. The selection of the most ideal refrigerant depends on the specific application, system design, safety requirements, cost-effectiveness, and availability [12]. This study presents a review of recent developments in environmentally friendly refrigerants for refrigeration and air conditioning purposes. Understanding the advantages and disadvantages of various refrigerants can help researchers, manufacturers, policymakers, and consumers make informed decisions about the best refrigerant for their specific applications. Further research is needed to develop novel refrigerants that meet both technological and environmental prerequisites for achieving sustainable refrigeration and air conditioning. Stakeholders can support a more environmentally friendly future by considering the environmental impact, safety, and energy efficiency of refrigerants while meeting the needs of refrigeration technologies.

The calculation sheets we present in this study, and which we cite in the literature, can be a useful calculation tool for manufacturers operating in the HVAC and refrigeration sector. Furthermore, their open-source nature allows companies to determine their own optimum refrigerant selections.

Including information on which applications the alternative refrigerants can be used in would be helpful for more informed refrigerant selection. However, this calculation software should include more alternative refrigerants; our work on this is ongoing.

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