IJARST

International Journal of Advanced Research in Science and Technology

https://doi.org/10.62226/ijarst20252593

ISSN 2319 – 1783 (Print)

ISSN 2320 – 1126 (Online)

Low Global Warming Potential (GWP) Refrigerants: Drivers of the Transition Towards Sustainable Air Conditioning

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ARTICLEINFO

Article history:

Received	25 Nov 2025
Accepted	09 Dec 2025
Available online	28 Dec 2025

Keywords:

Global Warming Potential (GWP), Kigali Amendment, Low-GWP Refrigerants, HFOs, Natural Refrigerants, Sustainable Air Conditioning, Montreal Protocol.

ABSTRACT

The refrigeration and air conditioning (RAC) sector is undergoing a radical transformation driven by global environmental agreements, most notably the Montreal Protocol and its amendments, such as the Kigali Amendment. This transformation aims to phase down hydrofluorocarbon (HFC) refrigerants with high global warming potential (GWP) and transition to low-GWP alternatives. This research highlights the key drivers of this transition – regulatory, environmental, technical, and economic – and provides a scientific analysis of the available alternatives, such as hydrofluoroolefins (HFOs), natural refrigerants (e.g., Ammonia, Carbon Dioxide, Hydrocarbons), and new blends. It also discusses the challenges associated with this transition, such as flammability, toxicity, cost, and the need for technical upskilling, and concludes with strategies for embracing this shift towards more sustainable air conditioning systems.

Introduction:

The refrigeration and air conditioning sector has long relied on synthetic refrigerants to meet the growing demand for cooling and heating. Following the successful phase-out of ozone-depleting chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) under the Montreal Protocol, hydrofluorocarbons (HFCs) were adopted as "ozone-safe" substitutes. However, it was later discovered that most HFCs have a very high Global Warming Potential (GWP), thousands of times greater than carbon dioxide. As the climate change crisis intensifies, addressing the impact of these refrigerants on the climate has become imperative, leading to the emergence of a new generation of environmentally friendly refrigerants.

Synthetic refrigerants are human-made chemical compounds engineered for use in refrigeration and air conditioning systems. They do not exist naturally and are produced through industrial chemical processes. Synthetic refrigerants like CFCs, HCFCs, and HFCs solved safety issues but created environmental problems, with HFCs being potent greenhouse gases with high Global Warming Potential (GWP).

Environmentally friendly refrigerants are substances used for cooling that have a minimal negative impact on the environment. This is primarily defined by having a zero Ozone Depletion Potential (ODP) and a very low or zero Global Warming Potential (GWP). Environmentally friendly refrigerants, including natural options (Ammonia, CO_2, Hydrocarbons) and new synthetics (HFOs), have zero Ozone Depletion Potential (ODP) and negligible GWP.

1- The Dual Climate Impact of RAC Systems

RAC is the standard acronym for Refrigeration and Air Conditioning.

RAC systems are technological assemblies that control the temperature, humidity, purity, and distribution of air within a defined space. Their primary function is to transfer heat from an area where it is undesirable (making it cooler) to another area where it can be rejected.

This process is based on the fundamental principles of thermodynamics and the refrigeration cycle, which involves the compression, condensation, expansion, and evaporation of a refrigerant.

RAC systems can be broadly categorized by their purpose:

– Refrigeration Systems Primarily designed to remove heat from a space or product to maintain a temperature below the surrounding ambient air. The focus is on preserving goods (e.g., food, medicine).

  domestic refrigerators, supermarket freezers, cold storage warehouses, industrial process cooling.

- Air Conditioning Systems: Designed to provide human comfort or a suitable environment for processes by controlling the temperature, humidity, and air quality within an enclosed space. They typically maintain a temperature close to or above the ambient for comfort.

  residential split AC units, commercial building HVAC systems, vehicle air conditioning, data center cooling.

The environmental impact of RAC systems is twofold:

1. Direct Impact caused by the leakage of high-GWP refrigerants into the atmosphere during operation, maintenance, or equipment disposal.

   In the context of Refrigeration and Air Conditioning (RAC) systems, Direct Impact refers to the contribution to climate change caused by the release of refrigerant gases directly into the atmosphere.

   The Direct Impact is the global warming effect resulting from the emission of high-GWP (Global Warming Potential) refrigerants from systems due to leaks, improper servicing, or disposal at the end of equipment life.

   - Mechanism when a synthetic refrigerant with a high GWP (such as R-410A, which has a GWP of 2088) escapes from a system, it acts as a potent greenhouse gas in the atmosphere, trapping heat thousands of times more effectively than carbon dioxide (CO_2).
   - Key Factor the magnitude of the Direct Impact depends entirely on the GWP of the refrigerant and the total amount leaked.

The Direct Impact is the damage done by the refrigerant gas itself when it leaks out of the system and into the air. This is the primary environmental reason for the global shift away from high-GWP HFCs towards lower-GWP alternatives like HFOs and natural refrigerants.

2. Indirect Impact resulting from the electrical energy consumption required to operate these systems. If the electricity source relies on fossil fuels, this contributes to CO_2 emissions.

   In the context of Refrigeration and Air Conditioning (RAC) systems, Indirect Impact refers to the contribution to climate change caused by the energy consumption of the system over its operational lifetime.

   The Indirect Impact is the total amount of carbon dioxide (CO_2) and other greenhouse gases emitted by the power plants generating the electricity required to run the system's compressor, fans, and controls.

   - Mechanism A significant portion of the world's electricity is generated by burning fossil fuels (coal, natural gas). The more energy an RAC system consumes, the more fuel must be burned, releasing CO_2 into the atmosphere.
   - Key Factor The magnitude of the Indirect Impact depends on the energy efficiency of the RAC system and the carbon intensity of the local electrical grid.

The Indirect Impact is the environmental damage caused by the power station smokestacks producing the electricity to run your air conditioner or refrigerator. A highly efficient system has a lower indirect impact.

The goal of transitioning to low-GWP refrigerants is to significantly reduce the direct impact, while maintaining or improving energy efficiency to minimize the indirect impact.

Direct vs. Indirect Impact

"Table 1"

Feature	Direct Impact	Indirect Impact
Source	Leakage of refrigerant gases from the system.	Energy consumption (electricity/fuel) of the system.
Primary Gas	Synthetic Refrigerants (HFCs, HFOs).	Carbon Dioxide (CO_2) from power generation.
Main Cause	Leaks, poor maintenance, improper disposal.	Low energy efficiency of the RAC system.
Where it Happens	At the RAC system location.	At the power plant generating the electricity.
Key Metric	GWP (Global Warming Potential) of the refrigerant.	Energy Efficiency of the system (e.g., COP, SEER).
Primary Goal	Use refrigerants with low GWP.	Use systems with high energy efficiency.

2- Drivers of the Transition to Low-GWP Refrigerants

Low-GWP Refrigerants are a class of cooling fluids used in refrigeration and air conditioning systems that have a minimal direct contribution to global warming when released into the atmosphere.

A low-GWP refrigerant is one with a Global Warming Potential (GWP) significantly lower than that of the traditional hydrofluorocarbons (HFCs) they are designed to replace. There is no universal threshold, but a GWP of less than 150 is often a target for many applications to be considered truly climate-friendly.

2.1 Regulatory Drivers and International Agreements

- The Kigali Amendment to the Montreal Protocol (2016): This is the most powerful global driver. It mandates more than 100 countries to phase down HFCs by over 80% over the next thirty years. Countries are divided into groups with different timelines, creating a clear framework for the industry.
- Regional and National Legislation Such as the European Union's F-Gas Regulation, which imposes strict limits on the use of high-GWP HFCs and promotes the use of alternatives. Many countries are adopting similar legislation governing production and consumption.

2.2 Environmental and Economic Drivers

- Environmental Pressures increasing public awareness and pressure from non-governmental organizations on the need to combat climate change.
- Green Building Requirements sustainable building projects (such as those seeking LEED certification) require the use of low-GWP refrigerants.
- Economic Efficiency in the long term, highly efficient natural refrigerant systems can save on energy operating costs, potentially offsetting the sometimes-higher initial investment.

3- Technical Alternatives: Available Low-GWP Refrigerants

Why Use Available Low-GWP Refrigerants?
The transition to available Low-GWP refrigerants is not a matter of choice but a necessary evolution for the RAC industry, driven by a combination of critical factors:

1. Future-Proofing and Market Competitiveness:
   - Avoiding Obsolescence equipment designed for phased-out refrigerants will become difficult and expensive to service as gas supplies dwindle and prices soar. Investing in low-GWP technology future-proofs new installations.
   - Meeting Market Demand green building standards (like LEED), corporate sustainability goals, and environmentally conscious consumers increasingly demand systems that use environmentally friendly refrigerants. Offering low-GWP solutions provides a significant competitive advantage.

2. Technical and Performance Benefits:
   - Superior Efficiency many low-GWP refrigerants, particularly natural refrigerants like R-717 (Ammonia) and R-290 (Propane), offer higher energy efficiency (a higher Coefficient of Performance - COP) than the HFCs they replace. This directly reduces electricity consumption, lowering operating costs and the system's Indirect Climate Impact.
   - Driving Innovation, the shift forces manufacturers to develop better, safer, and more efficient system designs, advancing the entire industry.

3. Economic Incentives and Risk Management:
   - Stable Pricing as high-GWP HFCs are phased down, their cost is becoming volatile and is expected to rise significantly. Low-GWP alternatives offer more stable long-term pricing.
   - Reduced Liability proactively managing environmental risks by using low-GWP refrigerants protects businesses from potential future carbon taxes or penalties associated with high-GWP leakages.

3.2 Hydrofluoroolefins (HFOs) and Blends
Hydrofluoroolefins (HFOs) are a class of synthetic refrigerants engineered as the fourth generation of fluorinated gases, designed specifically to address the high Global Warming Potential (GWP) of their HFC predecessors.
HFOs are unsaturated organic compounds composed of hydrogen, fluorine, and carbon, characterized by the presence of a double bond (C=C) in their chemical structure. This double bond allows them to react quickly with atmospheric hydroxyl radicals, causing them to break down in the atmosphere in a matter of days, rather than years.

- Characteristics such as R-1234yf and R-1234ze. They have a very low GWP (less than 1 to ~5). They are non-flammable or mildly flammable (A2L).
- Advantages their performance characteristics are similar to traditional HFCs, allowing for their use in existing equipment with some modifications. Ideal for mobile air conditioning and small systems.
- Challenges their cost is higher than traditional HFCs, and some are classified as "mildly flammable" (A2L), requiring additional safety measures.
- Primary Characteristic Ultra-low GWP (typically less than 1 to ~10) and Zero Ozone Depletion Potential (ODP).
- Safety Classification most are classified as A2L (Mildly Flammable), meaning they have a low burning velocity. This is a key trade-off for their low GWP.

HFOs are the new, ultra-low GWP synthetic refrigerants, but their mild flammability often leads to them being blended with other gases to create safer, practical, and more efficient replacements for the high-GWP refrigerants in use today.

3.3 Natural Refrigerants
Natural Refrigerants are substances that occur naturally in the environment and are used as working fluids in refrigeration and air conditioning systems.
They are naturally occurring molecules—not human-made synthetics—that have been harnessed for their thermodynamic properties to provide cooling. Their key environmental advantage is an exceptionally low or zero impact on global warming and ozone depletion.
Core Characteristics origin exists naturally in the environment (air, water, biological processes).

environmental Profile Possess zero Ozone Depletion Potential (ODP) and a very low or zero Global Warming Potential (GWP). No "Novel Entities" They are not part of the problem of introducing new, persistent human-made chemicals into the biosphere.
These refrigerants occur naturally and have very low or zero GWP.

- Propane (R-290) and Isobutane (R-600a):
  - Advantages high energy efficiency, GWP ~3, readily available and low cost.
  - Challenges highly Flammable (A3). They require special techniques to mitigate ignition risk, such as reducing refrigerant charge (mandated by standards like IEC 60335-2-40) and designing hermetically sealed systems.
- Ammonia (R-717):
  - Advantages exceptional energy efficiency, GWP = 0, high refrigeration capacity. Ideal for industrial applications and large commercial refrigeration.
  - Challenges toxic (B2L) and flammable at certain concentrations. They require highly integrated systems, good ventilation, and highly trained technical personnel.
- Carbon Dioxide (R-744):
  - Advantages Non-flammable, non-toxic, GWP = 1, ideal for high-ambient temperature applications (retail heat pumps).
  - Challenges It operates at very high pressures (up to 130 bar), requiring specially designed equipment. Its efficiency can drop in very hot climates.

3.4 Technical Alternatives Available Low-GWP Refrigerants
This table provides a technical comparison of the primary low-GWP refrigerant options, highlighting their key properties, advantages, and ideal applications.

"Table 2"

Refrigerant (Name/Class)	Safety Class (ASHRAE 34)	GWP (AR5)	ODP	Key Advantages	Key Challenges & Limitations	Primary Applications
Hydrocarbons (HCs)						
Propane (R-290)	A3 (Highly Flammable)	~3	0	Excellent energy efficiency, low cost, readily available, compatible with mineral oils.	High Flammability (A3) requires strict charge size limits (IEC 60335-2-40) and safety measures (e.g., no ignition sources, sealed components).	Domestic refrigerators, sma split AC units, commercial plug-in displays, dehumidifiers.
Isobutane (R-600a)	A3 (Highly Flammable)	~3	0	Slightly lower capacity than R-290, very high efficiency in small systems.	Same high flammability concerns as R-290; charge limits are even more restrictive.	Primarily domestic refrigerators and freezers.
New-Generation Synthetics						
HFOs (e.g., R-1234yf, R-1234ze)	A2L (Mildly Flammable)	<1	0	Ultra-low GWP, thermodynamic properties very similar to the HFCs they replace (e.g., R-134a).	Mild flammability (A2L) requires updated system design (e.g., leak detectors, burn-proof relays). Higher cost per kg.	Automotive air conditioning (R-1234yf), chillers, medium-pressure chillers (R 1234ze), foam blowing.
HFO/HFC Blends (e.g., R-454B, R-32)	A2L (Mildly Flammable)	~450-750	0	Designed as "near-drop-in" replacements for high-GWP HFCs (e.g., R-454B for R-410A). GWP is ~75% lower.	Still A2L flammable, requiring technician training. Not a simple "drop-in" for existing equipment; may require component changes.	New residential and commercial air conditioning systems (R-32, R-454B). Retrofits require careful engineering.
Natural Refrigerants						
Ammonia (R-717)	B2L (Toxic, Mildly Flammable)	0	0	Exceptional energy efficiency & heat transfer, low cost, easily detectable by smell.	Toxicity requires robust system design (indirect systems), ventilation, detectors, and highly trained personnel.	Large industrial refrigeratio plants (cold storage, food processing), ice rinks.
Carbon Dioxide (CO_2 / R-744)	A1 (Non-Toxic, Non-Flammable)	1	0	Non-flammable and non-toxic, good thermophysical properties, efficient in low-temperature applications.	Very high operating pressures (transcritical cycle). Efficiency can drop significantly in high ambient temperatures.	Commercial refrigeration (cascade systems, transcritical booster), heat pumps, transport refrigeration.

Summary of Key Trade-offs:

- Flammability vs. GWP: The lowest GWP options (R-290, R-744, R-717) come with significant trade-offs: high flammability (A3), high pressure (A1), or toxicity (B2L).
- The A2L Compromise: HFOs and HFO blends (A2L) offer a middle ground with significantly lower GWP and manageable, mild flammability, but they require a cultural shift in safety practices.

- Application is Key: There is no single "best" refrigerant. The optimal choice depends entirely on the application's scale, safety requirements, and ambient operating conditions.

4- Challenges and Barriers to Widespread Adoption

Challenges and Barriers to Widespread Adoption of Low-GWP Refrigerants

The transition to low-GWP refrigerants, while environmentally imperative, faces significant hurdles that slow down its widespread adoption across the industry.

1. Safety and Perception Challenges

- Flammability (A2L & A3) this is the single greatest barrier. Moving from class A1 (non-flammable) refrigerants to A2L (mildly flammable) and A3 (highly flammable) refrigerants like R-32, R-454B, and R-290 requires a fundamental shift in:
  - System Design need for leak detectors, sealed electrical components (burn-proof relays), improved ventilation, and charge limit compliance.
  - Handling Procedures strict protocols for installation, brazing, and recovery.
  - Risk Perception overcoming the fear and resistance from installers, building owners, and insurers regarding flammable gases.
- Toxicity (B2L) refrigerants like Ammonia (R-717) require specialized handling, complex system designs (often indirect), and highly controlled environments, limiting their use to large industrial applications with trained staff.

2. Economic and Market Barriers

- Higher Initial Cost:
- Refrigerant Cost new-generation synthetic refrigerants (HFOs) are currently more expensive to produce than established HFCs.
- Equipment Cost systems designed for low-GWP refrigerants often require more expensive components, such as pressure-resistant parts for CO_2 or explosion-proof electronics for flammable gases.
- Investment in Existing Infrastructure the vast installed base of equipment designed for HFCs represents a massive sunk cost. Retrofitting can be complex or impossible, making a swift transition economically challenging for many businesses.

3. Technical and Infrastructural Hurdles

- Lubricant and Material Compatibility new refrigerants may not be compatible with traditional mineral or alkylbenzene oils, requiring a shift to Polyol Ester (POE) oils, which are hygroscopic (absorb moisture) and demand stricter system cleanliness.
- Performance in High Ambients some alternatives, notably CO_2 (R-744), can see a drop in efficiency (COP) in high ambient temperatures, requiring sophisticated and expensive system controls to manage the transcritical cycle effectively.
- Lack of Standardized Components for newer refrigerants, especially CO_2, the supply chain for specialized high-pressure components may not be as mature or widespread, leading to longer lead times and higher costs.

4. The Human Factor knowledge and Training Gap

- Critical Skills Shortage the vast majority of the current workforce is trained exclusively on handling non-flammable HFCs. There is an urgent, global need for comprehensive training on:
- Understanding A2L and A3 safety protocols.
- Proper installation, leak detection, and recovery techniques for flammable gases.
- Servicing high-pressure CO_2 and toxic Ammonia systems.
- Resistance to Change technicians and engineers accustomed to the relative safety of HFCs may be hesitant or resistant to adopt new technologies they perceive as more dangerous or complex.

5. Regulatory and Standards Lag

- Outdated Codes and Standards many local building codes, safety standards, and insurance regulations were written for the era of A1 refrigerants. The widespread adoption of flammable refrigerants is often hindered until these codes are updated to reflect the safe handling practices for A2L and A3 class gases (e.g., revising charge limit tables based on new room size and ventilation calculations).

6. Supply Chain and Availability

- Limited Production Scale while growing, the global production capacity for some HFOs and their blends is not yet at the scale of traditional HFCs, which can affect availability and price.
- Market Fragmentation the diversity of "drop-in" alternatives can lead to confusion and a fragmented supply chain, with contractors

needing to stock multiple types of refrigerants for different equipment.

the widespread adoption of low-GWP refrigerants is critically hindered by a interconnected set of practical barriers. The foremost challenge is the significant safety paradigm shift required to manage flammable (A2L/A3) or toxic (B2L) alternatives, which demands a fundamental overhaul of technician training, installation practices, and building codes. This is compounded by substantial economic pressures, including the higher initial costs for both the new refrigerants and the specialized equipment they require. Furthermore, the transition is hampered by a pronounced skills gap within the workforce and a lag in the global supply chain for compatible components. Ultimately, overcoming these barriers is not merely a technical formality but a complex, systemic prerequisite for the industry to fully align with global environmental mandates and achieve a sustainable future.

5- Solutions to Challenges in Adopting Low-GWP Refrigerants

The following table maps specific challenges to actionable solutions:

"Table 3"

Challenge / Barrier	Proposed Solutions
1. Safety (Flammability & Toxicity)	• Develop & Enforce Updated Standards: Accelerate the global harmonization of safety standards (like ASHRAE 15, IEC 60335-2-40) that allow for larger, safe charge sizes of A2L/A3 refrigerants through better ventilation and leak detection requirements. • Engineering Controls: Mandate and integrate built-in safety features in equipment, such as automatic leak detectors, ventilation shut-offs, and sealed (burn-proof) electrical components. • Robust Risk Assessment: Promote the use of mandatory Job Safety Analysis (JSA) sheets for every task involving flammable refrigerants.
2. Economic & Cost	• Lifecycle Cost Analysis: Educate consumers and clients on the Total Cost of Ownership (TCO), highlighting long-term energy savings from high-efficiency natural refrigerants like R-290. • Financial Incentives: Governments and utilities should offer tax credits, rebates, or subsidies for purchasing low-GWP equipment and for proper disposal of old, high-GWP systems. • Economies of Scale: Support manufacturers in scaling up production of low-GWP refrigerants and components to drive down costs through increased market competition and volume.
3. Technical & Infrastructural	• Intensive, Hands-On Training: Shift from theoretical training to mandatory, practical, certified programs on safely installing, servicing, and recovering A2L/A3 refrigerants and high-pressure CO_2 systems. • Knowledge Transfer from Mature Markets: Utilize training resources and standards from regions leading the transition (e.g., Europe, Japan). • R&D Investment: Fund research into improving the high-ambient performance of CO_2 systems and developing new, safer refrigerant blends.
4. Knowledge & Training Gap	• Mandatory Certification: Implement a licensing system that requires technicians to be certified for specific refrigerant classes (A1, A2L, A3, B2L). • "Train-the-Trainer" Programs: Rapidly scale expertise by having manufacturers and industry bodies train a core group of master trainers who can then disseminate knowledge locally. • Integrate into Curricula: Incorporate modern refrigerant handling into the core curriculum of technical schools and vocational training centers.
5. Regulatory Lag	• Proactive Policy Making: Governments must work with industry experts to proactively update national building codes, fire safety codes, and equipment standards to safely accommodate new technologies. • Clear Phase-Down Roadmaps: Provide a clear, long-term schedule for HFC phase-down, giving the industry certainty to invest and plan.

overcoming the challenges to adopting low-GWP refrigerants demands a coordinated, multi-faceted strategy centered on proactive regulation, comprehensive education, and technological innovation. The safety concerns posed by flammability and toxicity can be mitigated through the rigorous implementation of updated international standards, the integration of engineered safety features like leak detection systems, and, most critically, the establishment of mandatory, hands-on certification programs for engineers and technicians. Economically, the higher initial costs must be addressed through financial incentives that highlight long-term energy savings and by scaling production to reduce prices. Ultimately, a successful transition relies on closing the knowledge gap through a systemic overhaul of technical training, ensuring the workforce is not only prepared but also confident in deploying these essential technologies to build a sustainable and compliant future for the cooling industry.

Conclusion:

The transition to low-global warming potential (GWP) refrigerants is an irreversible and necessary evolution for the refrigeration and air conditioning (RAC) industry, marking a pivotal shift from convenience-driven choices to responsibility-driven imperatives. This transformation, propelled by the landmark Kigali Amendment and global climate commitments, moves the sector beyond merely solving the ozone crisis to actively confronting its role in climate change. The journey entails a fundamental trade-off: moving away from the stable, high-GWP hydrofluorocarbons (HFCs) of the past towards a diversified portfolio of solutions, including ultra-low GWP synthetics like hydrofluoroolefins (HFOs) and the climate-neutral promise of natural refrigerants such as ammonia, carbon dioxide, and hydrocarbons. However, this path is not without significant hurdles. The widespread adoption of these alternatives is challenged by the critical barriers of managing flammability and toxicity, overcoming economic inertia, and bridging the profound knowledge and skills gap within the global workforce.

Ultimately, the success of this transition hinges on a synchronized, multi-stakeholder approach. Manufacturers must continue to innovate, designing safer and more efficient systems. Governments and regulatory bodies are tasked with creating a supportive framework of clear regulations, updated safety codes, and financial incentives. Most critically, the linchpin of this entire endeavor is workforce development. The role of engineers, trainers, and technicians is paramount; their commitment to continuous learning and adherence to new safety protocols will determine the safe, effective, and widespread deployment of these new technologies. By uniting regulatory direction, technological advancement, and comprehensive education, the RAC industry can successfully navigate this complex transformation. This is not merely a technical compliance exercise but a definitive opportunity to redefine its legacy, ensuring a sustainable, efficient, and climate-friendly future for essential cooling services worldwide.

References:

1. UNEP Ozone Secretariat. (2016). *The Kigali Amendment to the Montreal Protocol: HFC Phase-down*. United Nations Environment Programme. https://ozone.unep.org/treaties/montreal-protocol/kigali-amendment
2. European Parliament and Council. (2014). *Regulation (EU) No 517/2014 on fluorinated greenhouse gases and repealing Regulation (EC) No 842/2006 (F-Gas Regulation)*. Official Journal of the European Union.
3. ASHRAE Standard 34. (2019). *Designation and Safety Classification of Refrigerants*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.
4. IPCC. (2018). *Global Warming of 1.5°C. An IPCC Special Report*. Intergovernmental Panel on Climate Change. https://www.ipcc.ch/sr15/
5. Calm, J. M. (2008). The next generation of refrigerants – Historical review, considerations, and outlook. *International Journal of Refrigeration*, *31*(7), 1123-1133.
6. McLinden, M. O., Brown, J. S., Brignoli, R., Kazakov, A. F., & Domanski, P. A. (2017). Limited options for low global warming potential refrigerants. *Nature Communications*, *8*, 14476.
7. IEC 60335-2-40. (2022). *Household and similar electrical appliances – Safety – Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers*. International Electrotechnical Commission.
8. Bolaji, B. O., & Huan, Z. (2013). Ozone depletion and global warming: Case for the use of natural refrigerant – a review. *Renewable and Sustainable Energy Reviews*, *18*, 1-9.
9. Mota-Babiloni, A., Navarro-Esbrí, J., Barragán-Cervera, Á., Molés, F., & Peris, B. (2015). Analysis based on EU Regulation No 517/2014 of new HFC/HFO mixtures as alternatives of high GWP refrigerants in refrigeration and HVAC systems. *International Journal of Refrigeration*, *52*, 21-31.