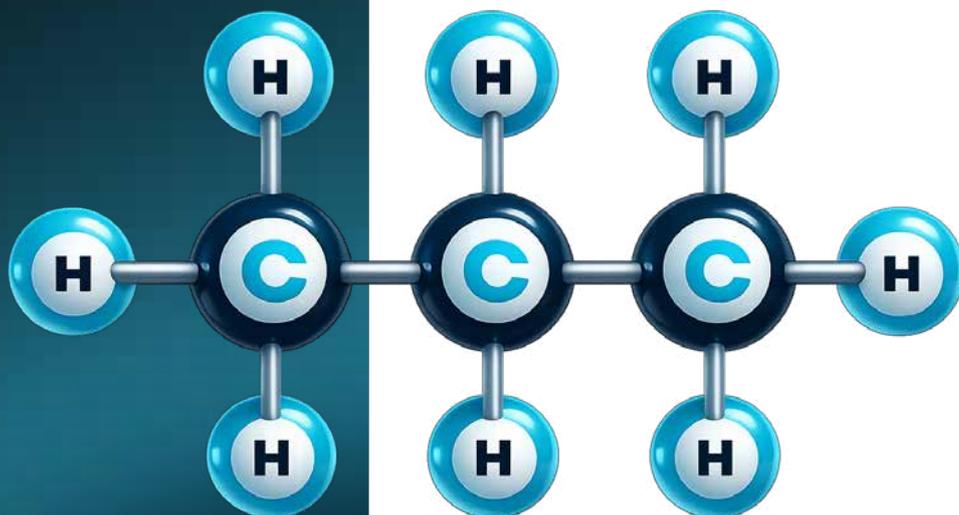




WHITE PAPER

R290

THE EVOLUTION OF REFRIGERANTS



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TABLE OF CONTENTS

1	INTRODUCTION	p. 4
2	HISTORICAL EVOLUTION OF REFRIGERANTS	p. 5
2.1	THE ERA OF SYNTHETIC REFRIGERANTS: CFCS, HCFCS, AND HFCS	p. 5
2.2	LATE 20TH CENTURY–PRESENT: HFCS, HFOS, AND THE RETURN TO NATURAL REFRIGERANTS	p. 5
2.3	INTERNATIONAL AND REGIONAL REGULATORY FRAMEWORK	p. 5
2.4	PFAS AND TFA: ENVIRONMENTAL AND REGULATORY IMPLICATIONS	p. 8
2.5	SUSTAINABILITY APPLIED TO REFRIGERANTS: THE TRIANGLE AND THE SEVEN FORCES MODEL	p. 8
2.6	TECHNOLOGICAL AND APPLICATION TRENDS	p. 9
2.7	FUTURE PROSPECTS, REGIONAL ADOPTION, AND DEVELOPMENT SCENARIOS	p. 10
2.8	CONCLUSION	p. 10
3	INSTALLATION REQUIREMENTS FOR PRODUCTS USING NEW A3 REFRIGERANTS: FOCUS ON R290	p. 12
3.1	INTRODUCTION	p. 12
3.2	ATEX DIRECTIVE	p. 12
3.3	UNIT INSTALLATION	p. 13
3.4	INTERNAL SAFETY FEATURES	p. 14
3.5	ALARM SEQUENCE AND MANAGEMENT	p. 14
3.6	EXAMPLES OF COMPLIANT INSTALLATIONS	p. 15
3.7	EXAMPLES OF NON-COMPLIANT INSTALLATIONS	p. 16
4	THE DIFFERENTIATING VALUE OF HIREF: PERFORMANCE, SUSTAINABILITY, AND MARKET EXPANSION	p. 17
4.1	VISION AND POSITIONING IN THE TRANSITION TO NATURAL REFRIGERANTS	p. 17
4.2	ENERGY PERFORMANCE AND TEWI REDUCTION	p. 17
4.3	EXPANSION OF MARKET SECTORS	p. 18
4.4	BENEFITS FOR DESIGNERS, INSTALLERS, AND END USERS	p. 18
4.5	APPLICATION CASES AND USE SCENARIOS OF HIREF WITH R290	p. 18
5	SUMMARY AND FUTURE OUTLOOK	p. 20

1 INTRODUCTION

The selection of refrigerants today represents a central issue not only for the ecological transition of the HVAC/R (Heating, Ventilation, Air Conditioning and Refrigeration) sector, but also for corporate competitiveness, operator safety, and environmental health. This white paper highlights the rapid transformation currently taking place in the refrigerants used within the HVAC sector: from the phase-out of high-environmental-impact refrigerants to the renewed adoption of “natural” refrigerants, as well as the increasingly stringent regulation on PFAS and the risks associated with new HFC/HFO blends. This document provides an in-depth and critical overview of these processes, integrating the main international legislative references together with emerging engineering and operational best practices.

2 HISTORICAL EVOLUTION OF REFRIGERANTS

2.1 The Era of Synthetic Refrigerants: CFCs, HCFCs, and HFCs

In the 1930s, chlorofluorocarbons (CFCs) were introduced, followed by hydrochlorofluorocarbons (HCFCs), stable compounds that are non-toxic and non-flammable. However, CFCs and HCFCs are responsible, respectively, for stratospheric ozone depletion and the greenhouse effect, leading to international agreements aimed at their phase-down and eventual phase-out.

2.2 Late 20th Century–Present: HFCs, HFOs, and the Return to Natural Refrigerants

Starting from the 1990s, increasing regulatory and scientific pressure led to the adoption of hydrofluorocarbons (HFCs), characterized by zero ODP (Ozone Depletion Potential) but often high GWP (Global Warming Potential). More recently, hydrofluoroolefins (HFOs) have gained traction due to their very low GWP; however, they are currently under scrutiny for the potential formation of by-products such as TFA (trifluoroacetic acid) and their classification within the PFAS family. In parallel, a renewed adoption of natural refrigerants—CO₂, ammonia, and hydrocarbons—is underway, driven both by technological innovation and by international regulatory requirements.

» Historical Timeline of Refrigerants

Period	Predominant Type	Main Refrigerants	Characteristics	Environmental Impact
1830 - 1930	Natural	NH ₃ , CO ₂ , SO ₂ , ether	Toxic / Flammable	Low GWP / Nothing
1930 - 1990	Synthetic	CFCs, HCFCs	Non-toxic / Safe	High ODP and GWP
1990 - 2010	Lower-impact synthetic refrigerants	HFCs	Non-ozone-depleting	High GWP
2010 - Today	New synthetic refrigerants / Return to natural refrigerants	HFOs, CO ₂ , NH ₃ , R290	Low GWP, zero ODP	Very low GWP

The timeline reflects an evolution driven by technical requirements, safety considerations, and, above all, regulatory frameworks, with a cyclical rediscovery of natural refrigerants enhanced by advances in system engineering.

2.3 International and regional regulatory framework

2.3.1 The Montreal Protocol and the Kigali Amendment

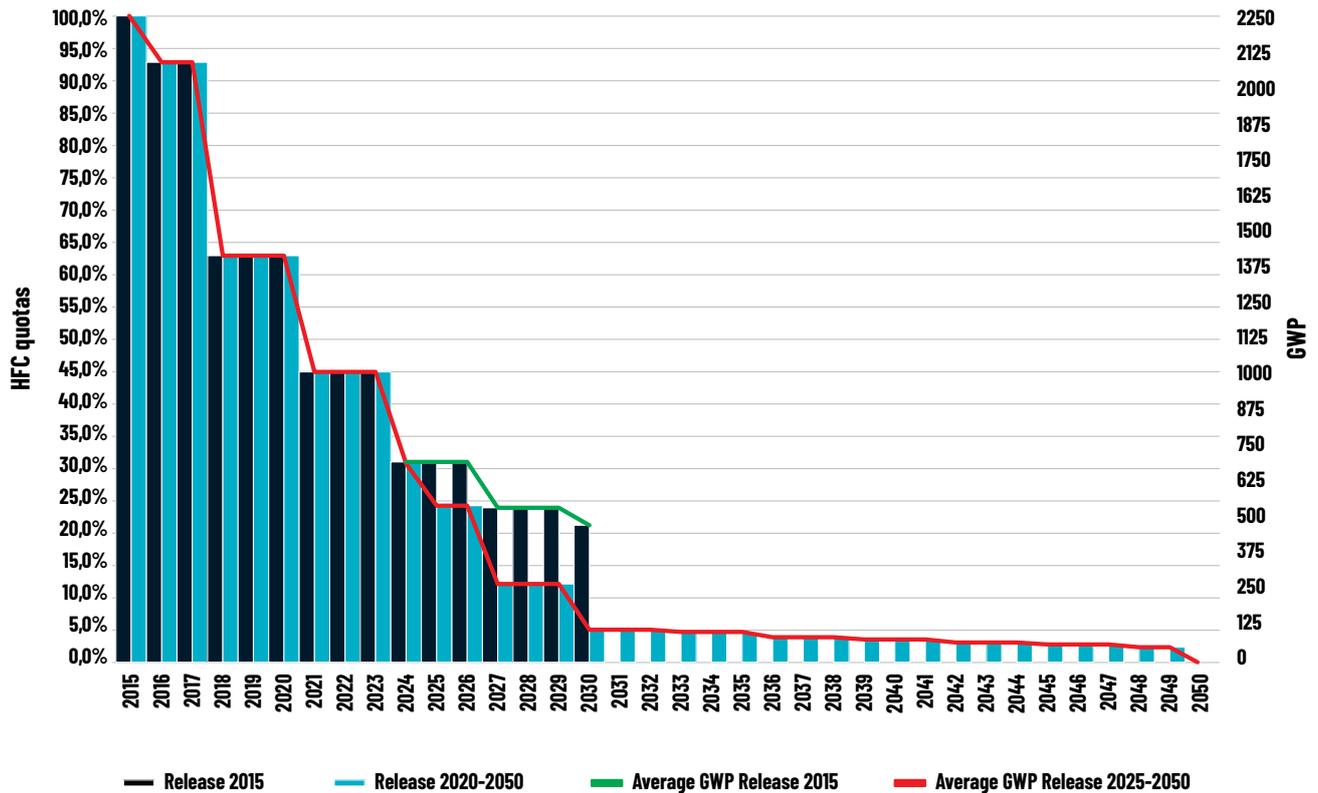
The Montreal Protocol (1987), a milestone in the fight against ozone depletion, mandated the gradual phase-out of CFCs and HCFCs. The Kigali Amendment (2016) extended the framework to HFCs, setting phase-down targets of 80–85% by 2047 for most developed economies, with a differentiated schedule for developing countries.

2.3.2 The F-Gas Regulation in Europe: EU Regulations 517/2014 and 573/2024

The European Union has introduced the most advanced and stringent legislation on fluorinated gases (“F-Gas Regulation”), initially with Regulation (EU) No 517/2014 and, as of March 2024, with the new Regulation (EU) 573/2024. The main developments include:

- Progressive reduction of the overall HFC quota expressed in CO₂ equivalent, reaching 24% by 2027 and 21% by 2030 (compared to the baseline period)
- Stringent GWP limits for the placing on the market of new equipment (e.g. GWP <150 from 2027 for small systems)
- Mandatory leak containment, electronic logbooks, and compulsory certification and training for operators
- Strong incentive for the adoption of natural refrigerants and very low-GWP HFOs

HFC phase down F-gas 2025-2050



» Bans effective from 1 January 2025

Monobloc units ≤ 12 kW	2027: GWP < 150 2032: Natural refrigerants
Monobloc units ≤ 50 kW	2027: GWP < 150
Monobloc units > 50 kW	2030: GWP < 150
Chillers ≤ 12 kW	2027: GWP < 150 2032: Natural refrigerants
Chillers > 12 kW	2027: GWP < 750
Air-to-water split systems ≤ 12 kW	2027: GWP < 150 2035: Natural refrigerants
Split systems > 12 kW	2029: GWP < 750 2032: GWP < 150

2.3.3 The United States: AIM Act, SNAP, and EPA

U.S. regulation is based on the American Innovation and Manufacturing (AIM) Act (2020), which mandates an 85% phase-down of HFCs by 2036 compared to baseline levels, and on the EPA’s SNAP (Significant New Alternatives Policy) rules, which approve new low-GWP alternatives (including the regulated use of A2L refrigerants).

» Table of refrigerants available from 1 January 2026

REFRIGERANT	GWP (AR4)	FLAMMABILITY CLASS
R410A	2088	A1
R134a	1430	A1
R513A	572	A1
R454B	467	A2L
R515B	299	A1
R454C	149	A2L
R1234ze	6	A2L
R1233zd	5	A2L
R290	3	A3
R600a	3	A3
R601a	3	A3
R744 (CO ₂)	0	A1

» Global reduction in the use of HFC refrigerants (EU, USA, Kigali)

REGION	START DATE	1st QUOTA REDUCTION	2nd REDUCTION	FINAL TARGET
EU (F-Gas 517/2014 & 573/2024)	2015	-7% (2016)	-37% (2018-2020)	-79% (2030), phase-out by 2050
USA (AIM Act)	2022	-10%	-30% (2024)	-85% (2036)
Kigali Amendment	2019-2024	Multiple phases		80-85% (2047; 2048 for Asia/MEA)

The table shows how the regulatory transition is underway on a global scale, with progressive reductions in the available HFC quotas.

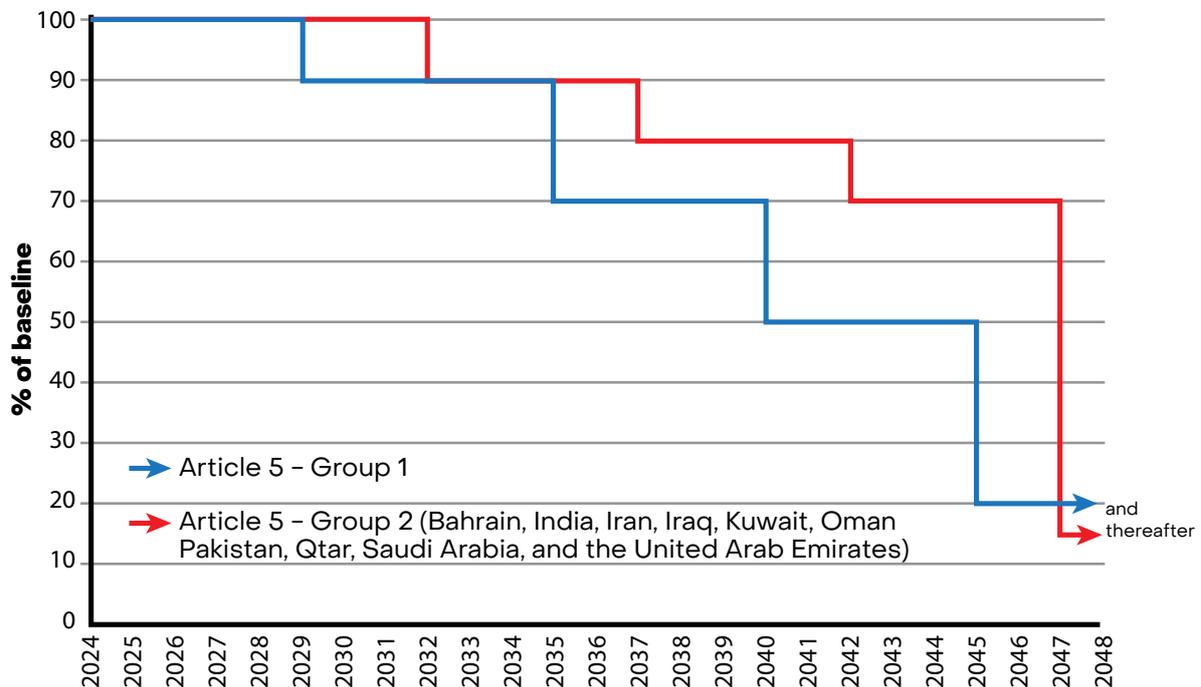
2.3.4 Kigali Amendment

Kigali Amendment: HFC phase-down in Article 5 and non-Article 5 countries

» Kigali Amendment

Baseline and gradual reduction expressed as CO ₂ e	Article 5 countries (developing countries) – Group 1	Article 5 countries (developing countries) – Group 2	Non-Article 5 countries (developed countries)
Baseline formula	Average HFC consumption for the 2020–2022 period + 65% of the HCFC baseline	Average HFC consumption for the 2024–2026 period + 65% of the HCFC baseline	Average HFC consumption for the 2011–2013 period + 15% of the HCFC baseline
Freeze	2024	2028	-
1st step	2029 - 10%	2032 - 10%	2019 - 10%
2nd step	2035 - 30%	2037 - 20%	2024 - 40%
3rd step	2040 - 50%	2042 - 30%	2029 - 70%
4th step	-	-	2034 - 80%
Plateau	2045 - 80%	2047 - 85%	2036 - 85%

» Phase-down schedule



* For Belarus, the Russian Federation, Kazakhstan, Tajikistan, and Uzbekistan, the HCFC component of the baseline is set at 25%, and three different initial steps are planned:

- 1 5% reduction in 2020,
- 2 35% reduction in 2025, and
- 3 85% reduction by the end of 2036.

Group 1: Article 5 Parties that are not part of Group 2.

Group 2: Countries with High Ambient Temperatures (HAT – High Ambient Temperatures): Bahrain, India, the Islamic Republic of Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates.

2.3.5 REACH Regulation and PFAS restriction in Europe

At the same time, the REACH initiative aims to introduce a broad restriction on PFAS, covering more than 10,000 substances, including many next-generation fluorinated refrigerants. The proposal предусматривает transitional periods and technical derogations that are difficult to negotiate, and risks excluding from the market even low-risk fluoropolymers, which are critically used in components and sealing applications.

2.3.6 PFAS regulation in the United States and elsewhere

The United States is evaluating similar restrictions, while the State of Maine has already set a ban, effective in 2040, on the sale of refrigerants with intentionally added PFAS. Regulatory approaches to PFAS and degradation products such as TFA vary significantly across different jurisdictions.

2.3.7 From the 19th Century to the Early 20th Century: Natural Refrigerants

Refrigeration systems originated in the 19th century with the use of natural fluids such as ammonia (R717), carbon dioxide (R744), ether, sulfur dioxide, and methyl chloride. Although thermodynamically efficient, these refrigerants posed significant toxicity and flammability risks, which over time led to the search for safer alternatives for residential and commercial applications.

2.4 PFAS and TFA: Environmental and Regulatory Implications

2.4.1 PFAS: what they are, where they are found, and environmental risks

PFAS, or per- and polyfluoroalkyl substances, include both polymers (such as PTFE, PVDF, etc.) and fluorinated refrigerants, including HFOs and their blends. They are characterized by high persistence (resistance to degradation), environmental mobility, and accumulation, particularly in water bodies. The main risks are associated with chronic impacts on the environment and human health, as well as with the difficulty of remediation.

2.4.2 PFAS in refrigerants and their impact on HVAC/R technologies

PFAS are widely used in:

- As refrigerants (many HFCs/HFOs and blends);
- In component materials (gaskets, valves, seals, PTFE- and PFPE-based lubricants). The proposed REACH restriction, if adopted without technical exemptions, would have devastating effects on the industry and risks halting more than 90% of current applications in RACHP systems.

2.4.3 TFA and HFOs: by-products and critical issues

TFA (trifluoroacetic acid), a by-product of HFO degradation, is highly persistent and soluble, with risks of accumulation in water bodies and impacts that are not yet fully understood. The widespread use of HFC/HFO blends, while representing a measure to mitigate global warming, could lead to the diffuse formation of TFA, with potential long-term repercussions on the environment and human health.

» Environmental and regulatory impacts of PFAS and TFA

Sostanza / Applicazione	Environmental Impact / Persistence	Current Regulatory Status
PFAS in refrigerants	Extreme persistence; mobility	EU proposal for a total restriction
HFOs (e.g. R1234yf, R1234ze)	Degradation products such as TFA are persistent and soluble	Under monitoring and pending regulatory limits
Technical fluoropolymers	Persistent, but neither toxic nor bioaccumulative	Some derogations under discussion

The regulatory framework requires a more granular assessment balancing actual risk, irreplaceable performance, and supply chain sustainability.

2.5 Sustainability applied to refrigerants: the triangle and the Seven Forces model

2.5.1 Il triangolo sostenibile: sicurezza, impatto ambientale, costo

In the modern refrigerant landscape, sustainability is no longer defined solely in terms of GWP and ODP. The “sustainability triangle” identifies three key factors:

- Safety: toxicity, flammability, operating pressure
- Environmental impact: ODP, GWP, TFA/PFAS potential

- Cost: initial investment, energy consumption, life-cycle cost

The objective is to identify the optimal trade-off among these parameters, taking into account application-specific and regulatory requirements.

2.5.2 The Seven-Forces Model in HVAC/R Refrigerant Selection

Refrigerant selection decisions must integrate:

1. Regulatory frameworks / regulatory pressures (Kigali Amendment, F-Gas, AIM Act, REACH)
2. Safety (flammability, toxicity)
3. Energy efficiency (COP, EER)
4. Compatibility and ease of retrofit
5. Cost and availability of the refrigerant
6. Broader environmental impact (ODP, GWP, TFA/PFAS generation)
7. Technological innovation (instrumentation, controls, smart solutions)

This framework enables the sustainability of each solution to be assessed in relation to all stakeholders across the value chain.

» Seven-Forces Model (Diagram)

Force	Impact on refrigerant selection
Regulatory framework	Compliance, restrictions, exemptions, future availability
Operational safety	Fire / explosion / toxicity risks, technical requirements
Energy efficiency	Overall system TEWI, COP, heat recovery systems
Compatibility / Retrofit	Ease of system conversion, technical expertise
Cost and availability	Price, supply chain, maintenance and replacements
Extended environmental impact	ODP, GWP, TFA / PFAS risk, soil / water accumulation, disposal
Innovation	New architectures, digitalization, smart monitoring

2.6 Technological and application trends

2.6.1 A2L and A3 refrigerants: characteristics, safety and regulations

A2L (LOW FLAMMABILITY): HFOS & R32

A2L refrigerants are characterized by low toxicity and mild flammability (higher LFL, L = low burning velocity). Typical examples include R1234yf, R32 and R454B. Made available through the introduction of updated safety standards (EN 378, IEC 60335), they offer thermal performance comparable to HFCs, with GWP <150–700 and higher energy efficiency than many natural refrigerants, with risks that can be managed through updated system layouts and components.

A3 (HIGH FLAMMABILITY): HYDROCARBONS

Hydrocarbons (R290 – propane, R600a) are highly flammable, with regulatory charge limits and design variations required by EN 378 and the ATEX Directives. However, they are

unmatched in terms of GWP (equal to 3) and efficiency in small- and medium-capacity equipment.

2.6.2 Transcritical CO₂: technology and applications

Transcritical CO₂ (R744) systems are now widely adopted in commercial and industrial refrigeration across Europe, North America, Japan and Australia. Key features include:

- GWP = 1 (no significant greenhouse effect);
- High operating pressure (90–130 bar), requiring advanced design and control;
- Highly efficient heat recovery (“heat reclaim”);
- Very attractive performance in temperate/cold climates, with further improvements in hot climates thanks to technologies such as ejectors, parallel compression and chill boosters.

2.6.3 Hydrocarbons (propane R290, isobutane R600a): potential and limitations

Hydrocarbons, being natural refrigerants with near-zero GWP impact, are well suited for domestic refrigeration, small-scale commercial refrigeration, monoblock heat pumps and small industrial units. Limitations include stringent safety requirements (A3 classification), the need for flameproof components and operator training, as well as typical restrictions on the allowable refrigerant charge.

2.6.4 HFOs and HFC/HFO blends: trends, outlook and limitations

HFOs are highly promising due to their low GWP and good compatibility; however, their mild flammability and the potential to generate TFA keep them under regulatory scrutiny. They are also widely used in HFC/HFO blends (e.g. R454B), which act as transitional solutions by ensuring compatibility, lower retrofit costs and improved efficiency compared to legacy systems, while still remaining at risk in the event of PFAS bans.

» Comparative table of the main refrigerants for HVAC/R applications

Refrigerant	Safety class	ODP	GWP	Main applications	Advantages	Limits
CO ₂ (R744)	A1	0	1	Large-scale retail, food industry, heat pumps	No climate impact, safe	High pressures, complexity / efficiency
Propane (R290)	A3	0	3	Small to medium capacity, chillers, heat pumps	Very high efficiency, low cost	Flammable, charge limits, safety
R32	A2L	0	675	Heat pumps, air conditioning	High efficiency, pressure similar to R410A	Highly flammable, moderately high GWP
R1234yf/ze	A2L	0	4/7	Automotive, small-scale refrigeration, chillers	Very low GWP, compatible	Mild flammability, potential TFA formation?
R410A (HFC)	A1	0	2088	Legacy systems, being phased out	Non-flammable, well-known performance	High GWP, regulatory restrictions
R454B	A2L	0	531-700	Retrofit, commercial applications	System compatibility, medium GWP	Mild flammability, PFAS concerns in the future?
R454C	A2L	0	147	Heat pumps, air conditioning, commercial applications	Low GWP	Temperature glide, mild flammability, PFAS concerns in the future?

» Refrigerant application matrix, efficiency and limitations

Application	Preferred refrigerant	Primary rationale
Residential air conditioning	R32, R290, HFO	Efficiency, GWP, safety
Data center	HFO, CO ₂	Efficiency, GWP, safety
Commercial refrigeration	CO ₂ , R290, HFO-HFC/HFO blends	GWP regulations, efficiency
Industrial refrigeration	NH ₃ , CO ₂	Performance, zero ODP/GWP
Automotive	R1234yf, CO ₂	Regulatory compliance, technical compatibility

2.7 Future prospects, regional adoption, and development scenarios

2.7.1 Europe

Europe continues to lead the transition with the most restrictive (and accelerated) HFC phase-down, the rapid adoption of CO₂ and hydrocarbons, increasing pressure on PFAS and the promotion of natural refrigerants even in medium- to large-scale applications. The new F-Gas Regulation (EU) 2024/573 and the proposed REACH restrictions on PFAS represent a paradigm shift: over the next 5–10 years, the vast majority of new installations will need to be compatible with non-fluorinated refrigerants or with specific HFOs that are not classified as PFAS.

2.7.2 United States

The HFC phase-down is following a tight schedule towards an 85% reduction by 2036. The AIM Act and SNAP rules will expand the range of accepted A2L and natural refrigerants, although local regulatory barriers (state-level regulations) and the PFAS framework are still evolving. Major retail chains and food processors are also driving the adoption of CO₂, NH₃ and hydrocarbons in the USA.

2.7.3 Asia and emerging markets

Adoption timelines are more gradual, but the pressure from multinational HVAC/R companies, the presence of major manufacturers and the convergence towards Kigali parameters are expected to drive a rapid acceleration already from 2026–2028, particularly in China and Southeast Asia, both

in the retail sector and in industrial applications. In India, the Gulf region and Africa, Kigali roadmaps are more extended.

2.7.4 Applications: trends by sector

- Commercial/retail refrigeration: CO₂ is now mainstream in Europe and increasingly adopted in the USA. Hydrocarbons are rapidly gaining ground for plug-in applications.
- Industrial refrigeration: ammonia and CO₂ are strengthening their leadership also in cold storage, food and beverage, and pharmaceutical applications.
- Air conditioning: R32 and HFOs in Asia and the USA; in Europe, transition towards R290 (propane) for small/medium systems and a mandatory GWP <150 by 2027.
- Automotive: R1234yf and CO₂, with increasing focus on lifecycle impact and overall energy efficiency.
- Datacenters: HFOs (R1234ze) predominantly, with CO₂ used to a more limited extent for high-capacity chillers. R513A and R454B are adopted as drop-in solutions and for lower capital investment costs.

2.8 Conclusion

The refrigerant sector is undergoing the fastest and most profound transition in its history. Increasingly stringent European and national regulations, concerns related to PFAS and TFA, and the pressure of climate urgency are driving an irreversible technological and managerial shift. Refrigerant selection can no longer be based solely on GWP, but must be assessed within the safety–environment–cost triangle.

- The short- to medium-term outlook foresees:
- Dominance of “natural” refrigerants (CO₂, propane, ammonia) in almost all new applications, especially in Europe and in the industrial/commercial sector.

- Growth of A2L solutions (R454B, HFOs, blends) supported by stringent safety measures, but with a limited horizon set by the evolution of European PFAS regulations.
- Gradual but irreversible phase-out of high-impact fluorinated refrigerants, both in the EU and in the USA and other advanced countries, with rapid extension to emerging markets.

Challenges remain: safety, training, transition costs, and the presence of obsolete systems requiring technical and economic compromise solutions, pending a new generation of truly “future-proof” refrigerants and HVAC/R systems that deliver high performance while respecting the environment and public health. Innovation, supported by a global regulatory vision, represents the main pathway forward.

3 INSTALLATION REQUIREMENTS FOR PRODUCTS USING NEW A3 REFRIGERANTS: FOCUS ON R290

3.1 Introduction

HiRef units charged with R290 refrigerant are designed in compliance with applicable European regulations, in particular EN378-3.

This document is intended as a guideline for the designer and installer in the installation and use of equipment containing highly flammable and explosive refrigerant fluids (A3 according to ISO 817:2014).

3.2 ATEX Directive

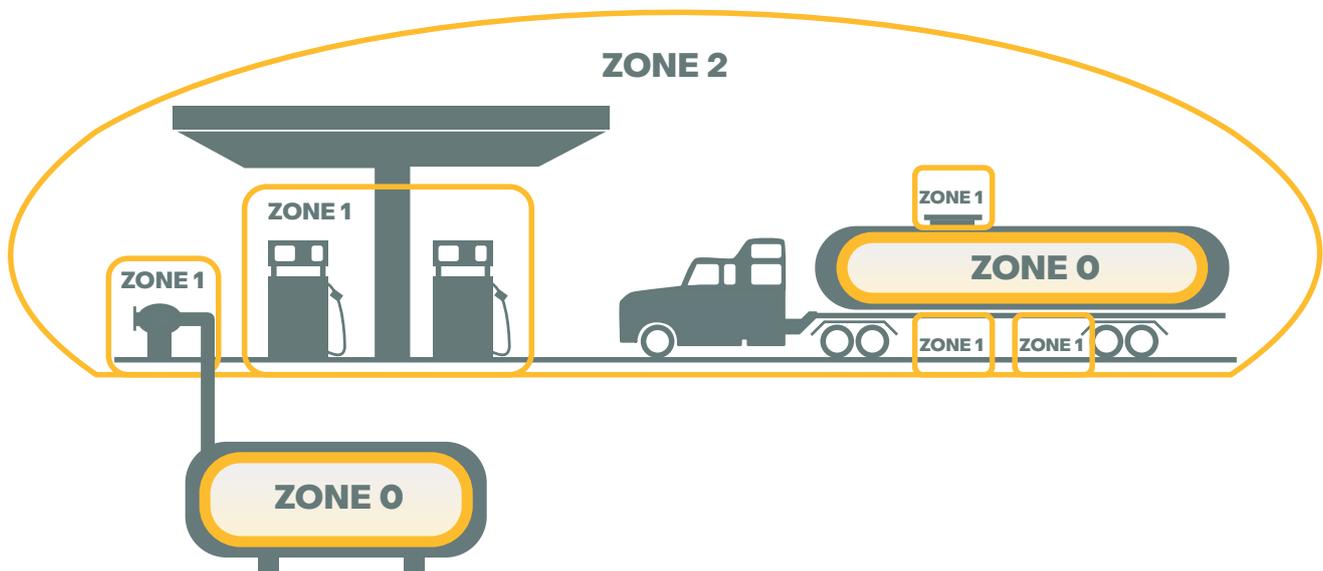
The ATEX Directive 2014/34/EU defines the minimum health and safety requirements for workplaces with the presence of potentially explosive atmospheres; in particular, it divides them into zones, depending on the likelihood of the presence of an explosive atmosphere, and specifies the criteria according to which products are selected within these zones.

» ATEX Symbol



» CLASSIFICATION OF INSTALLATION ZONES

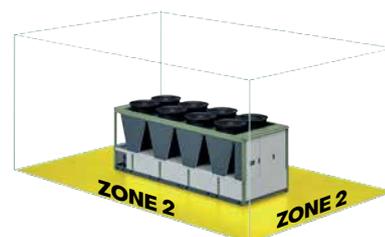
Zone	Description	Presence of gas
Zone 0	Area in which an explosive atmosphere consisting of a mixture of air and flammable substances in the form of gases, vapour or mist is present either permanently or for prolonged periods or frequently.	> 1000 hours/year
Zone 1	Area in which, during normal activities, the formation of an explosive atmosphere, consisting of a mixture of air and flammable substances in the form of gas, vapour or mist is likely to occur.	10 to 1000 hours/year
Zone 2	Area in which, during normal activities, the formation of an explosive atmosphere, consisting of a mixture of air and flammable substances in the form of gases, vapour or mist is not likely, and may only occur for short periods of time.	< 10 hours/year



In general, HVAC systems are rigid and the joints used between refrigerant containing parts are usually 'durably technically tight' as defined in EN 1127-1:2019. The ATEX zone that generates after the loss of refrigerant from one of these systems is classifiable as type 2 zone.

The use of gas detectors consolidates the concept of 'durably technically tight' by monitoring the tightness of the joints. If a leak is detected, all components with ignition sources must be shut down according to safety standards.

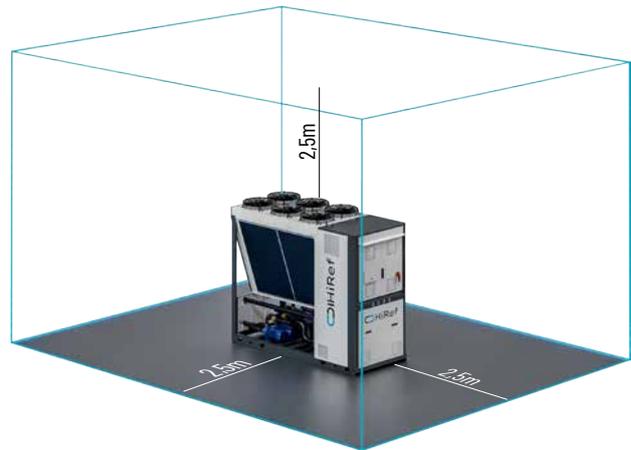
Example ATEX zone for a heat pump



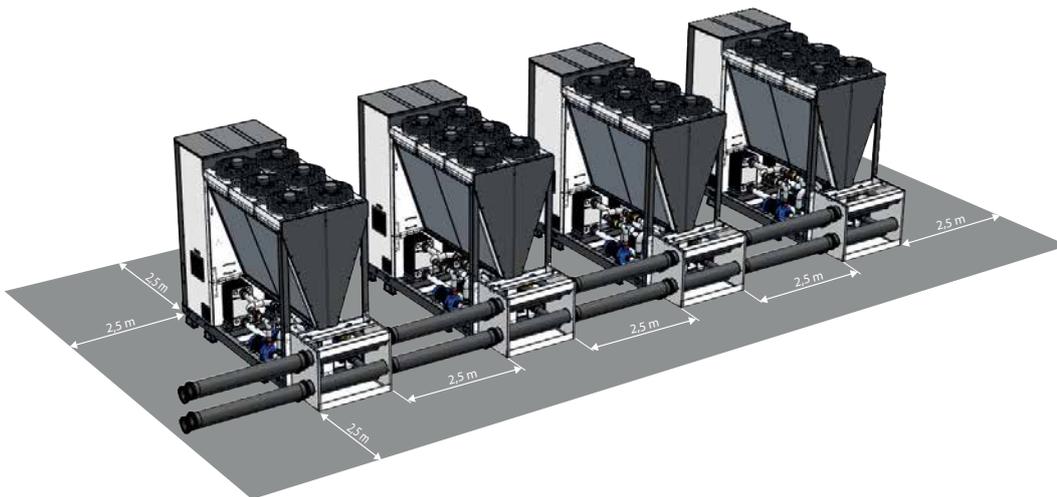
3.3 Unit installation

Units loaded with A3 (highly flammable) gas must be installed away from drains, manholes, drainage channels and any other element that could act as a potential escape route for any leakage of said gases, which must always be considered FLAMMABLE and heavier than air. The minimum distance to be maintained with respect to these requirements is 2.5 metres. Within this safety zone, it is strictly forbidden to smoke, use open flames or carry out any work that may generate flames, arc discharges or sparks.

Safety area – single installation example



Safety area – multiple installation example



ATTENTION

When installing multiple units in close proximity, the minimum distance between units must be 2.5 meters. This distance can be reduced to 1.5 meters provided that, in the event of a refrigerant leak alarm on any of the units, all machines are shut down. To enable this function, an electrical interconnection between the units in the group is required, to be carried out EXCLUSIVELY by trained personnel or authorized service centers (after specific training on the procedure).

4. Restricted access to the machine room and signage with appropriate warning notices;
5. Emergency stop devices located outside the room.

3.3.1 Installation of units in indoor spaces

When installing units with A2L/A3 refrigerants in indoor spaces, the reference standard for determining the safety measures to be applied in the machine room is EN378-3. Specifically, the designer must provide for:

1. Adequate installation spaces, calculated based on the refrigerant charge of the largest circuit;
2. ATEX mechanical ventilation;
3. Refrigerant leak detection in the environment;

3.4 Internal safety features

3.4.1 Conveyance of safety valves

The unit's refrigeration circuit is equipped with **safety valves** for both the high-pressure and low-pressure sides. The connection point of the valves and their respective dimensions are indicated in the detailed drawings attached to these instructions.

The installer/end user must implement a discharge pipe of equal or greater size to the outlet of the safety valves, so as to **lead the discharge point away from the unit and other potentially triggering elements (4 metres minimum distance in all directions from the point of emission)**.

The emission point must be oriented upwards (and therefore protected with a removable cap or other equivalent element that, while allowing any expelled gases to escape, prevents rain, insects or contaminants from entering the pipe).

It is preferable to position the vent point above the roof, at a height of at least 5m above ground level.

If the piping length is particularly long (>10 m in total), it is recommended to provide a slight slope (1%) in the horizontal sectionsto facilitate the drainage of any condensate, and a trap must be created near the discharge point as shown in the following image, with a hole drilled at its base.

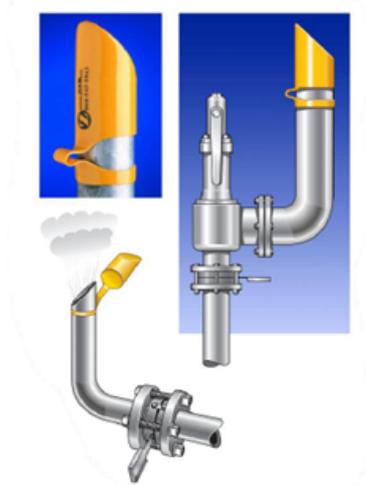


Image for illustrative purposes only.

3.4.2 Unit power supply

Units filled with an A3-rated refrigerant (typically R290, a highly flammable fluid) are equipped with a dual power supply line: a MAIN line to operate the units, and an AUXILIARY line to power the safety devices (described below):

- compressor compartment ventilation system;
- internal LEL (Lower Explosive Limit) detection sensor.

3.4.3 Hydraulic accessories

A degassing device or vent shall be installed to prevent the risk that, in the event of a heat exchanger failure, the refrigerant may contaminate the hydraulic circuit



3.5 Alarm sequence and management

In case of refrigerant leakage, the sensors are set to:

1. Provide an alarm signal when 10% of the LEL is reached;
 2. provide a shutdown signal upon reaching 20% of the LEL.
- The shutdown signal will implement a safety interlock with the upstream power supply of the unit. This interlock will safely and effectively cut the MAIN power, thereby shutting down and stopping the unit; only the AUXILIARY power will remain active to maintain both the ventilation inside the compressor box(es) and the functionality of the LEL sensors. Follow the instructions below in the event of a refrigerant leak signal from the sensors installed on the machine or possibly present near the machine:

In the event of an alarm for reaching the first LEL threshold (10%), it indicates that the unit is releasing a limited amount of refrigerant, but the situation regarding explosion risk is not critical. However, even a limited refrigerant leak is a situation that:

- will lead to a progressive loss of the refrigerant charge, and over time the unit will reach a condition where it can no longer perform its function; the user must take appropriate precautions to manage the process to which the unit is connected;
- could escalate to a more serious situation if the point from which the refrigerant gas is leaking were to expand (for example, due to erosion).

In any case, the user:

- technical support must be contacted;
- must not approach or stay near the unit

A remote refrigerant alarm signal is required (in addition to the three red, white and green LEDs on the front of the electrical panel) so that it is not necessary to approach the unit in the event of an alarm. This remote signal can be implemented by:

- via a remote display, available as an option and purchasable at any time by contacting the HiRef after-sales center;
- through remote monitoring of the unit's alarms (e.g., via ModBus or Ethernet) and configuring a dedicated remote hazard signal to be activated in the event of an alarm.

⚠ ATTENTION

When the second LEL threshold (20%) is reached, it indicates that the unit is releasing a significant amount of refrigerant, and the situation regarding explosion risk may become critical.

The safety interlock implemented on the MAIN power supply system will result in the complete shutdown and cessation

of operation of the unit (except for sensors and compressor room ventilation).

In any case, the user:

- technical support must be contacted;
- Do not approach or remain near the unit.

Technical support, when alerted for any type of alarm:

- must carry out inspection and maintenance activities using portable LFL/LEL detection devices at all times; maintenance on the unit is strictly prohibited while any concentration exceeds 5% of the LFL (measurements must be taken at multiple points of the unit, particularly the lower areas of the compressor box and the condenser coil compartment);
- When the LFL level is therefore below 5%, the unit must be completely evacuated of refrigerant; only after full evacuation, and while still observing the previous safety requirements, can repair and/or sealing restoration work on the unit be carried out;
- Once the repair and/or sealing restoration of the unit has been completed, the unit can be refilled and subsequently put back into service.

3.6 Examples of COMPLIANT installations



3.7 Examples of NON-COMPLIANT installations



In this case, HiRef did not authorize startup and required the installer to electrically interconnect the units. In the event of an alarm on any of the units on site, all units are automatically shut down. Only the power supply for safety systems, such as the refrigerant leak detection sensors and the emergency ventilation system, remains active.

4 THE DIFFERENTIATING VALUE OF HIREF: PERFORMANCE, SUSTAINABILITY, AND MARKET EXPANSION

We foresee a future in which the HVAC&R sector will increasingly play a decisive role in sustainable development.

We work to ensure that the Earth's resources are preserved for future generations and to give them the opportunity to achieve their own personal development.

Systems designed ad hoc following in-depth analysis are the result of data that reflect efficiency, innovation and circularity.

We believe in innovation driven by cross-sector contamination: we absorb the strengths of other industries with the aim of enhancing our expertise and maximizing performance. Collaboration with our partners and with the companies within our Group represents our most important asset, and we believe that, together, energy consumption can be optimized and the future can become fully sustainable.

We anticipate change and go beyond predefined solutions, leveraging the strength of lateral thinking.

4.1 Vision and positioning in the transition to natural refrigerants

HiRef's vision is based on an integrated approach to sustainability that encompasses environmental, economic and social dimensions. The company has chosen to focus on natural refrigerants such as propane (R290) and CO₂ (R744), drastically reducing the Global Warming Potential (GWP) of its systems and promoting a circular economy model. The use of natural refrigerants such as R290 involves specific safety challenges, mainly related to flammability and refrigerant charge management. These critical aspects have been addressed through the implementation of a range of technical and procedural solutions that ensure full compliance with European and international regulations, in particular the EN 378 series and the ATEX Directive.

This strategy translates into a product range that not only minimizes direct greenhouse gas emissions but also optimizes energy performance throughout the entire lifecycle, as confirmed by the application of LCA (Life Cycle Assessment) methodologies and the calculation of TEWI (Total Equivalent Warming Impact).

We have differentiated ourselves from competitors through our ability to customize solutions, avoiding a "catalogue-based" approach and offering tailor-made systems for data centers, industry, tertiary applications and critical infrastructures. The flexibility and vertical integration of in-house expertise, combined with a network of complementary companies (shall we mention the other companies?), enable us to cover a wide range of applications, from precision air conditioning for IT environments to industrial cooling and integrated energy management (Energy Loop).

At the international level, we have strengthened our presence across the EMEA, APAC, LATAM and South African regions through a commercial strategy that leverages both direct sales and collaboration with distributors and local subsidiaries.

Finally, the establishment of DataDom, specialized in turn-key prefabricated containerized data centers, represents an example of how HiRef is expanding its product and service portfolio to meet the new demands of the global market.

4.2 Energy performance and TEWI reduction

One of the most relevant aspects in the selection of natural refrigerants is the improvement of energy performance and the reduction of the overall environmental impact, measured through the TEWI (Total Equivalent Warming Impact) index. HiRef has developed solutions that maximize energy efficiency and minimize direct and indirect emissions, offering tangible advantages compared to traditional refrigerants.

TEWI CALCULATION

$TEWI [kgCO_2] = (\text{direct effect}) + (\text{indirect effect}) = mr * GWP + mCO_2 * \tau * e$

with:

- mr = mass of refrigerant released into the atmosphere during the unit lifecycle [kg];
- GWP = global warming potential of the refrigerant relative to the greenhouse potential of carbon dioxide (which is therefore assigned a GWP value of 1), typically evaluated over a 100-year time horizon [$kgCO_2/kg$];
- mCO_2 = mass of CO₂ emitted per unit of electrical energy [$kgCO_2/kWh$]; it depends on the power generation mix of each country and, more specifically, on the particular energy source (fossil, renewable);
- τ = unit lifecycle [years];
- e = annual electrical energy consumption [$kWh/year$].

THERMODYNAMIC PROPERTIES OF R290

Propane (R290) stands out for its excellent thermodynamic properties:

- Extremely low GWP, compared to values of 467 for R454B and 2088 for R410A;
- Lower operating pressures compared to R454B and R410A, reducing stress on components and improving system durability;
- High discharge temperature, up to 80°C, enabling the production of domestic hot water and heating water even in systems with traditional radiators, thereby expanding energy retrofitting opportunities;
- Higher COP (Coefficient of Performance) in many operating conditions, with energy efficiency 5–20% greater compared to synthetic refrigerants.

SYNERGISTIC TECHNOLOGIES

In our R290 units, we integrate advanced technologies to optimize energy performance:

- Oversized EC fans: enable precise modulation of the air flow rate, reducing energy consumption (up to 10% compared to AC fans) and noise levels;
- Finned coil condensers with 7 mm tubing: increase heat exchange efficiency and enable operation even at high

outdoor temperatures, allowing a reduction in refrigerant charge (up to 12%);

- Advanced electronic control with proprietary software: intelligent load management, integration with supervision systems, and optimization of operation based on operating conditions;
- Inverter-driven and on/off scroll compressors: high efficiency, redundancy/modulation capability and precise setpoint control, reducing seasonal energy consumption (up to 15%).

4.3 Expansion of market sectors

The transition towards low-GWP refrigerants (R1234ze) and natural refrigerants such as R290 is significantly expanding the range of market sectors accessible to HiRef solutions. High efficiency, application flexibility and regulatory compliance enable the company to meet the requirements of a wide spectrum of customers, from data centers to the manufacturing industry, from advanced tertiary applications to critical infrastructures.

DATA CENTERS AND IT INFRASTRUCTURES

Data center cooling represents one of the most dynamic, rapidly evolving and strategic markets for HiRef. Increasing power density, the exponential growth in data demand and the expansion of artificial intelligence require high-efficiency, low environmental impact cooling solutions. HiRef provides systems for liquid cooling, full-inverter chillers using low-GWP refrigerants, and advanced energy management systems (HiNode), ensuring very low PUE (Power Usage Effectiveness) values and maximum operational reliability.

INDUSTRY AND PRODUCTION PROCESSES

In the industrial sector, the demand for HVAC solutions is primarily driven by decarbonization requirements (European Green Deal) and energy optimization. HiRef units using R290 are applied in process cooling, air conditioning of production/commercial environments and heat recovery, offering advantages in terms of reduced operating costs and compliance with environmental regulations.

ADVANCED TERTIARY SECTOR AND CRITICAL INFRASTRUCTURES

HiRef solutions are applied in commercial buildings, hospitals, schools, hotels, telecommunications infrastructures and transport facilities. The ability to produce hot water at high temperatures, together with the low noise levels and modularity of the units, enables the company to meet the comfort, safety and sustainability requirements demanded by these sectors.

4.4 Benefits for designers, installers, and end users

The adoption of HiRef solutions using the natural refrigerant R290 provides a range of tangible benefits for all stakeholders across the value chain: designers, installers, energy managers and end users. These advantages translate into

higher efficiency, cost reduction, simplified procedures and improved environmental sustainability.

BENEFITS FOR DESIGNERS

- Wide design flexibility: the modularity of HiRef units allows the solution to be tailored to the specific site requirements, with the possibility of customization and integration with supervision and energy management systems;
- Guaranteed regulatory compliance: the units are designed in accordance with EN 378 and Directive 2014/34/EU (ATEX), simplifying project documentation and the declaration of conformity;
- Technical support and training: HiRef provides specialist consultancy and dedicated training courses on R290, facilitating skills development and the management of new technologies.

BENEFITS FOR INSTALLERS

- **Simplified installation procedures:** R290 monoblock units feature a hermetically sealed refrigerant circuit and are designed to minimize leakage risks, reducing on-site risk assessments and operational complexity;
- **Reduction of leak inspection obligations:** thanks to the low GWP and the limited refrigerant charge, R290 units are often exempt from the mandatory periodic leak checks required for HFCs, simplifying management and reducing recurring costs;
- **Training and certification:** HiRef promotes refresher and certification courses for installers and maintenance technicians, in line with the latest European and national regulations.

BENEFITS FOR END USERS

- Higher energy efficiency: R290 units ensure energy savings of up to 20% compared to traditional solutions, resulting in reduced operating costs;
- Lower environmental impact: the near-zero GWP and TEWI reduction contribute to environmental sustainability and facilitate access to incentives and green certifications;
- Application versatility: the ability to produce hot water at high temperatures makes HiRef solutions suitable also for existing systems with radiators, simplifying energy retrofitting;
- Reduced regulatory risks and future replacement costs: the adoption of R290 anticipates upcoming regulatory restrictions, avoiding the need for medium-term replacements and protecting the value of the investment.

In conclusion, HiRef solutions using R290 represent a strategic choice for all stakeholders in the HVAC value chain, offering tangible benefits in terms of efficiency, safety, sustainability and regulatory compliance.

4.5 Application cases and use scenarios of HiRef with R290

HiRef's experience in implementing solutions with natural refrigerants has resulted in a range of successful application cases, highlighting the versatility and effectiveness of the proposed technologies. The following sections analyse

several significant use scenarios, with a focus on data centers, industry, tertiary applications and energy retrofitting.

DATA CENTERS IN CENTRAL AND NORTHERN EUROPE

HiRef has contributed to the development of data centers in Central and Northern Europe by supplying innovative solutions for cooling and energy management. The project involved the installation of full-inverter chillers using low-GWP refrigerant (R1234ze), glycol-free free cooling systems and intelligent management through HiNode. The N+1 configuration and full redundancy ensured operational continuity, while the adoption of advanced technologies enabled the achievement of very low PUE values (<1.20) and maximum sustainability.

INDUSTRY AND PRODUCTION PROCESSES

HiRef units using R290 are employed for industrial process cooling, cold storage rooms, production lines and high power-density environments. The modularity of the solutions and the possibility of customization allow specific customer requirements to be met, ensuring energy efficiency, safety and regulatory compliance.

ENERGY RETROFITTING OF RESIDENTIAL AND COMMERCIAL BUILDINGS

HiRef heat pumps using R290 are applied in the energy retrofitting of existing buildings, enabling the replacement of traditional boilers and integration with radiator-based systems. The ability to produce hot water at high temperatures and the superior efficiency facilitate access to incentives and the reduction of energy costs.

SPECIAL APPLICATIONS AND INTERNATIONAL PROJECTS

HiRef has executed air conditioning projects for transport infrastructures (Copenhagen Metro), Formula 1 teams, and major telecommunications companies, all using CO₂ chillers, demonstrating the ability to adapt natural refrigerant solutions to highly critical and regulatory-complex environments.

These application cases demonstrate how HiRef low environmental impact solutions are able to address the challenges of the energy transition, offering tangible benefits in terms of efficiency, sustainability and safety across a wide range of operational contexts.

5 SUMMARY AND FUTURE OUTLOOK

HiRef technological solutions using natural refrigerants, particularly R290 and CO₂, represent the state of the art in the HVAC sector, combining energy efficiency, safety, sustainability and application flexibility to address the challenges of the energy transition and decarbonization. The company's vision, advanced technical architecture, regulatory compliance and benefits for all stakeholders strengthen HiRef's position as an innovative leader, ready to anticipate the needs of designers, energy managers and technical decision-makers in a rapidly evolving market.

The adoption of R290 enables a drastic reduction in GWP and TEWI, improves energy performance, provides access to new markets and application scenarios, simplifies system management and maintenance, and protects the value of investments in the long term. Operator training and certification, combined with the specialist consultancy offered by HiRef, facilitate the transition and ensure the safety and quality of installations.

Looking ahead, the ongoing regulatory evolution, the growing demand for sustainable solutions and technological innovation are opening new opportunities for HiRef and for the entire HVAC sector, with propane (R290) set to become the reference refrigerant for future air conditioning applications.



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