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UNDER THE AUSPICES

MINISTERO DELL'AMBIENTE
E DELLA SICUREZZA ENERGETICA



THE FUTURE OF REFRIGERATION AND SUSTAINABLE COOLING



THE KIGALI
AMENDMENT
2016-2026



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FOREWORDS

Greetings from the Minister



With EU Regulation 2024/573, Europe has profoundly reshaped the European legal framework governing refrigerant gases. The decision to rapidly phase out the use of current refrigerants due to their high climate impact and replace them with alternatives with zero or low climate impact entails technological, economic and commercial challenges. Just over two years after the Regulation entered into force, the Italian industry is addressing this transition with its customary determination and capacity for innovation and renewal. We are entering a decisive phase, as many of the requirements set out in the Regulation will enter into force in 2026 and 2027.

Over these two years of intensive work, the Ministry of the Environment and Energy

Security has supported the refrigeration sector through the challenging process of implementing the new legislation, acting as an advocate with the European institutions for interpretative solutions capable of addressing the inevitable difficulties that the application of the new rules has posed for Italian and European industry, while fully respecting the climate objectives.

2026 will also mark the full implementation of European rules into the Italian legal system, with the preparation of a new Presidential Decree to replace the current Presidential Decree No. 146 of 2018.

This will be an essential step to enable the thousands of refrigeration professionals to operate in full compliance with European legislation.

At the same time, we are aware that Europe's decision to move beyond the era of climate-damaging refrigerants has led to a worrying increase in illegal trade, managed by transnational criminal organisations.

In this regard, MASE, as the National Competent Authority, has taken decisive and effective action, working in cooperation with the Customs and Monopolies Agency, the Carabinieri NIPAAF and NOE units, and the Guardia di Finanza.

Among the most significant new initiatives is the establishment of a coordination table on F-Gas controls, aimed at developing new methodologies and tools, creating a network of technical analysis laboratories, facilitating the exchange of data and information, planning inspection and enforcement campaigns, and promoting training and awareness-raising on the issue.

These coordination efforts have already produced significant results, with the seizure of dozens of tonnes of illegally traded refrigerant gases of foreign origin across virtually the entire country.

Much work remains to be done, but it is encouraging to see growing awareness among businesses, industry professionals and Italian citizens of refrigeration-related issues: the need to phase out current refrigerants because of their serious climate impact, and the importance of choosing legally traded refrigerant gases.

Awareness, institutional coordination, attention to the productive sector, and determined action against illegal activities are the key elements for achieving these objectives.

Gilberto Pichetto Fratin
Minister of the Environment and Energy Security of Italy



FOREWORDS

10 Years of the Kigali Amendment: Delivering Climate Action through Partnership, Compliance, and Innovation



Ten years ago, Parties to the Montreal Protocol adopted the Kigali Amendment, expanding the treaty's environmental leadership to address climate change. By committing to phase down hydrofluorocarbons (HFCs), potent greenhouse gases widely used in refrigeration, air conditioning, and other cooling applications, governments once again demonstrated the power of multilateral cooperation to advance sustainable solutions.

A decade later, the Kigali Amendment stands as a landmark achievement in global environmental governance. Its implementation is accelerating the transition to sustainable cooling and is projected to avoid up to 0.5°C of global warming by the end of the century. Its success extends beyond compliance targets and regulatory milestones. It is reflected in the efforts of policymakers, customs officers, refrigeration and air-conditioning technicians, trainers, industry representatives, and especially National Ozone Officers, whose leadership has been essential in translating international commitments into effective national action and preparing countries for the long-term transition to sustainable cooling.

As an Implementing Agency of the Multilateral Fund, UNEP's Law Division, through its OzonAction programme, has supported developing countries throughout this transition. Through implementation of national projects and Compliance Assistance Programme (CAP) services, OzonAction has helped countries strengthen policies, address technical and regulatory challenges, and exchange practical experiences and lessons learned.

This support has become increasingly important as countries pursue multiple development and environmental objectives simultaneously. The transition to low-global-warming-potential technologies offers an opportunity not only to reduce climate impacts, but also to improve energy efficiency, strengthen climate resilience, enhance food and health systems, and support sustainable economic growth. As global demand for cooling continues to rise, effective implementation of the Kigali Amendment is critical to maximizing these broader benefits.

The progress achieved over the past decade has been made possible through the commitment of Parties, the Multilateral Fund, implementing and bilateral agencies, industry partners, training institutions, civil society, and countless professionals working across the cooling sector. Together, they exemplify the enduring strength of the Montreal Protocol model, which combines science, policy, finance, technology, and capacity building to deliver measurable environmental results.

As we celebrate this milestone, we can take pride in the achievements of the past ten years while looking confidently to the future. The Kigali Amendment continues to demonstrate that with strong partnerships, practical compliance support, and sustained commitment, global environmental challenges can be transformed into opportunities for climate action, sustainable development, and lasting benefits for future generations.

Patricia Kameri-Mbote,
Director, Law Division, United Nations Environment Programme (UNEP)



FOREWORDS

Thank you Kigali, where to focus next?

Ten years after the adoption of the Kigali Amendment, the refrigeration sector can look back on a decade of important progress. The Amendment created much more than a timetable for phasing down hydrofluorocarbons. It provided a direction for governments, industry, researchers and international organisations, encouraging innovation and placing sustainable refrigeration applications firmly within the global climate agenda. This anniversary is therefore an opportunity both to recognise what has been achieved and to consider what must come next.



Over the past decade, the Kigali Amendment has accelerated the transition towards refrigerants with a lower climate impact and encouraged the development of more efficient technologies. It has stimulated investment, strengthened cooperation and supported the adoption of new policies, standards and practices. The sector has demonstrated its ability to innovate and adapt, while continuing to provide services that are indispensable to society.

Refrigeration is fundamental for preserving food, protecting medicines and vaccines, ensuring safe working and living conditions, supporting industrial processes and helping communities cope with rising temperatures. It is also central to economic and social development. Our ambition must therefore be not only to reduce the environmental impact of the sector, but also to ensure that sustainable refrigeration applications remain reliable, affordable and accessible to all. It is a fundamental right.



Despite the progress made, the transition remains complex in some regions. Cooling demand continues to rise, while many countries still face limited access to efficient technologies, suitable financing and adequately trained professionals. The introduction of alternative refrigerants also requires appropriate safety standards, updated regulations and strong technical competence. At the same time, ageing or inefficient equipment, refrigerant leakage and inadequate end-of-life management continue to undermine environmental gains.

The coming decade must move us from commitment to full implementation. The HFC phasedown should be accompanied by a determined effort to improve energy efficiency throughout the lifetime of equipment. Policies addressing refrigerants and energy use should be better aligned, supported by reliable data and adapted to national circumstances. Greater attention must also be given to maintenance, leak prevention, refrigerant recovery, recycling and responsible disposal. People will remain at the heart of this transformation. Technicians, engineers, researchers and policymakers need the knowledge and skills to select, install and operate new technologies safely and effectively. Investment in training, certification and knowledge exchange must therefore be considered a strategic priority, particularly in developing countries. No single organisation or country can achieve this transition alone. Stronger cooperation between governments, industry, academia, professional associations and international institutions will be essential. The International Institute of Refrigeration will continue to support these collective efforts by advancing scientific knowledge, sharing expertise and connecting research, policy and practice.

The Montreal Protocol and its Kigali Amendment has shown what can be achieved when the international community acts with a common purpose. Its next chapter must ensure that climate ambition is translated into practical, inclusive and lasting solutions. We need a stable climate and better lives for all.

Yosr Allouche
Director General, International Institute of Refrigeration (IIR)

FOREWORDS

Empowering the RACHP workforce for the global transition



The challenges of climate change and the commitments under the Montreal Protocol and its Kigali Amendment require a global effort to phase out ozone-depleting substances and phase down HFCs, while meeting the growing demand for refrigeration, air conditioning and heat pumps. This transition depends on skilled technicians who can safely handle alternative refrigerants, reduce emissions and improve energy efficiency. Empowering the RACHP workforce is therefore essential to protecting our planet.

This commitment is at the heart of Centro Studi Galileo's work and this International Special Issue. Education must keep pace with technological change, connecting international expertise with technicians' everyday needs. Practical training, knowledge sharing and cooperation between institutions and industry turn environmental objectives into effective action.

We are currently carrying out numerous projects with UNEP, UNIDO and UNDP, supporting workforce development across continents. These collaborations bring together trainers, technicians, national authorities and local organisations to strengthen technical capacity and improve refrigeration practices. Training local trainers enables knowledge to spread through national training centres and professional networks, extending the benefits well beyond individual courses.

Recent training activities delivered by Centro Studi Galileo and ATF, the Italian association of RACHP technicians, include:

- **Philippines:** training for 50 trainers in Manila with UNIDO and TESDA, covering good servicing practices and the safe handling of low-GWP and flammable refrigerants.
- **Rwanda:** practical training on sustainable cooling, maintenance, refrigerant recovery, leak prevention and energy efficiency, within the CCAC/UNEP-funded project implemented by ICU with REMA and CSG.
- **Burkina Faso, Tunisia and other African countries:** training on good refrigeration practices, safe refrigerant handling and energy efficiency, alongside support for local training centres and the development of technicians' competencies.
- **Bhutan:** training in Thimphu on maintenance best practices and energy efficiency in refrigeration and air conditioning.
- **Bangladesh:** a UNEP-promoted Train-the-Trainers programme implemented by ATF, covering servicing, refrigerant recovery, energy efficiency and safe handling of flammable refrigerants, alongside training centre assessments and institutional discussions.
- **International ToT for women:** a UNEP-promoted programme hosted at CSG in Casale Monferrato for 11 women trainers from Bangladesh, Bhutan, China, the Maldives, Mongolia and Nepal. The programme combined



technical training, teaching methods and theoretical and practical assessment to support national training and certification systems. Alongside training, we assess training centres, review national legislation and support its practical implementation. We have also developed certification schemes to verify technicians' competencies through theoretical and practical assessment. By working with national authorities, training institutions and industry, we help strengthen training facilities, prepare trainers and assessors, and establish clear competency requirements.

This integrated approach connects technical education, legislation and implementation, supporting safe working practices and the effective application of environmental commitments.

We are also participating in IMPACT-F, a Horizon Europe project developing a global modelling platform to assess how cooling policies affect F-Gas emissions, energy demand and decarbonisation.

Bringing together fourteen partners, the project combines scientific analysis with dedicated training to support informed decisions and effective climate action around the world.

These activities share a common purpose: ensuring that people have the skills to deliver sustainable cooling. Governments should support training and certification, industry should contribute technical expertise and equipment, and employers should invest in continuous professional development.

The future of the RACHP sector depends on a competent and growing workforce. Through international cooperation, practical education and credible certification, we can help technicians meet changing demands and make safe, efficient and sustainable cooling more widely available.

**Marco Buoni, Board Member with "International Affairs" Mandate - Air conditioning and Refrigeration European Association (AREA)
CEO Chief Executive Officer - Centro Studi Galileo (CSG)**

The Kigali Amendment at Ten: Intelligent Cooling in a Warming World



Maria Socorro Manguiat

*Deputy Executive Secretary,
Ozone Secretariat, UNEP*

2026 has been marked by record-breaking heatwaves and other extreme weather events such as intense summer wildfires in Australia and South America, alongside catastrophic heavy rainfall and displacement across southern Africa. Temperatures in the northern hemisphere have soared past historic highs, pushing power grids towards maximum capacity, straining household budgets and stretching health facilities.

As temperatures increase, cooling has become a matter of survival. Yet the very technologies that provide relief—air conditioners, refrigerators, and cold chains—can worsen the climate crisis as the vast majority of equipment still relies on hydrofluorocarbons (HFCs), greenhouse gases thousands of times more potent than carbon dioxide. This is the paradox the parties to the Montreal Protocol on Substances that Deplete the Ozone Layer were faced with more than a decade ago, and one they were determined to solve. The Montreal Protocol, adopted in 1987, had already proven itself as one of the most successful environmental treaties in history. By phasing out ozone-depleting substances, it has put the Earth's protective shield on a clear path to recovery by mid-century and prevented up to 1°C of warming. In 2007, a scientific study quantified that the Protocol had already avoided 135 gigatonnes of CO₂-equivalent emissions (equal to the greenhouse gas emissions of more than 28.5 billion cars driven in one year) through the phase-out of 99 per cent of ozone-depleting substances under the Protocol. The remaining 1 per cent is largely hydrochlorofluorocarbons (HCFCs), which are expected to be phased out by 2030.

But as chlorofluorocarbons (CFCs) started to disappear, their replacements, HFCs, rose rapidly. While harmless to the ozone layer, they are powerful greenhouse gases. By 2009, another study projected that the use of HFCs and emissions from such use were set to surge in the coming decades in response to the regulations to phase out CFCs. Alarm bells started ringing!

NEGOTIATING THE KIGALI AMENDMENT

Diplomatic momentum began with small island states. In 2009, the Federated States of Micronesia and Mauritius tabled the first proposal to bring HFCs under the Montreal Protocol. A year later, the United States, Canada, and Mexico followed with a joint proposal. Progress was slow.

Many countries argued that HFCs were not ozone depleting and therefore outside the Protocol's scope. In the early years of discussions, some parties could not even agree to formally negotiate on the possibility of HFCs being included in the list of controlled substance under the Protocol. The turning point came in 2015, when a new study projected that HFCs alone could add 0.5 °C of warming by 2100. This evidence was described by negotiators as the "smoking gun." At the Twenty Seventh Meeting of the Parties in Dubai, governments agreed to formally discuss a possible amendment to the Protocol relating to HFCs. Negotiations were arduous and long. Every detail mattered: phase down schedules, financial support, technology pathways, and economic impacts. One negotiator described the process as "a chessboard limitlessly complex". By October 2016, after seven years

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of debate, the breakthrough came at the Twenty-Eighth Meeting of the Parties in Kigali, Rwanda when an amendment to phase down HFCs was adopted. Since entering into force in 2019, the Kigali Amendment has driven over 170 nations to legally commit to an 80–85 per cent phase down of HFCs by the late 2040s. Full ratification and implementation of the Amendment could avoid up to 0.5 °C of warming by 2100—potentially double if paired with a transition to more efficient cooling technology.

IMPACTS OF THE KIGALI AMENDMENT

The Kigali Amendment's design goes further than tackling the production and consumption of HFCs and the reduction of HFC-23 emissions. It promotes the transition to equipment using refrigerants with low or zero global warming potential (GWP) that are also being built to be more energy efficient. This means that air conditioners and refrigerators that move away from the use of HFCs generally consume less electricity. As a consequence, power grids face less stress, households save money, and emissions from fossil fuels decline. The benefits go beyond emission reductions and energy efficiency. The transition is also creating jobs. Additional technicians are being trained worldwide. Manufacturing hubs are producing more equipment that use natural refrigerants, while companies are investing in research and development. Frameworks to integrate Kigali goals are helping to ensure that construction of new buildings use efficient cooling with low GWP refrigerants.

Safety standards have been rewritten to address flammability and toxicity risks of alternatives to HFCs, mandating improved ventilation, leak detection, and charge limits. Energy efficiency laws now complement refrigerant regulations, requiring better insulation, smarter thermostats, and passive cooling design. For developing countries (Article 5 parties), ratification of the Kigali Amendment has opened access to financial and technical assistance, helping modernise industries and

enhance the skills of workers in the refrigeration, air conditioning and heat pump (RACHP) sector. For developed countries (Article 2 parties), ratification provides a head start in deploying new technologies, securing export advantages in global markets. Implementation of the Kigali Amendment and its impacts are gaining traction. Across regions, parties are advancing their Kigali implementation plans and HFC phase down strategies. Countries are pairing ratification with legislation mandating HFC reductions, unlocking investment and green jobs. In Asia, for example, governments are aligning national cooling action plans with Kigali timelines and investing in natural refrigerants and technician training, while in Africa, innovation coupled with performance standards has driven affordable access to efficient cooling through financing schemes and pilot schemes to support equipment replacement. These short-term benefits are immediate, slowing near term warming while the longer-term benefits are transformative, preventing up to half a degree of warming by 2100.

A FUTURE WORTH BUILDING

The successes to date are noteworthy but can be accelerated with additional capacity and support to address transition challenges. While the economic benefits are clear, there are short-term costs for long-term financial gain. Replacing old systems is costly. Most companies cannot simply switch refrigerants and technologies; they must be replaced or heavily retrofitted with specialised components designed to handle high pressures or prevent explosions, especially in hot climates.

As is often the case, new ideas face market obstacles. Alternative refrigerants—natural options such as ammonia or propane, which are toxic or flammable, respectively—face technical challenges that need to be addressed if consumer trust is to be gained. Constraints on the supply of low- and zero-GWP refrigerants and lower production volumes keep market prices high. Regulatory

reform and the corresponding institutional capacity to set change in motion requires time and can bring about higher consumer prices and industrial costs in the short term. Despite some of these challenges, the Kigali Amendment's impacts are measurable and demonstrable.

THE NEXT CHAPTER

Ten years on, the Kigali Amendment is a triumph of collaboration and cooperation. Nations once more came together to solve a problem that impacts everyone. It is a story of intelligent cooling in a warming world. It shows that action can be pragmatic, equitable, and effective. It also proves that cooperation can deliver results even when headlines are dominated by division and multilateralism is under strain. Continued success will require political will, institutional participation, and support from science, industry, and business. Together, the Montreal Protocol and its Kigali Amendment do far more than guide the transition to climate friendly refrigerants. They drive innovation in cooling technologies, strengthen regulatory frameworks, support improvements in servicing, and safeguard both ozone and climate integrity. Implementation is everything. The Montreal Protocol reversed ozone depletion because it was universally ratified. The same must happen for the Kigali Amendment. As we face escalating heatwaves, wildfires and droughts coupled with rising cooling demand, the Amendment's legacy is clear: sustainable cooling is not just possible, it is a necessity, is already underway and needs to maintain momentum. Full implementation is key. If nations stay the course, the Kigali Amendment will be remembered not just as a quiet success, but as one of the greatest environmental achievements of our time.



A Global Overview of Recent Technological Developments in the RACHP Sector



Yosr Allouche

Director General,
International Institute
of Refrigeration (IIR)

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International cooperation as an enabler of technological transition

The refrigeration, air conditioning and heat pumps (RACHP) sector has significantly evolved. Its infrastructure has become fundamental for modern societies. They preserve food and medicines, maintain safe and productive indoor environments, enable industrial processes and technological development, and increasingly provide an efficient route for the electrification of heating. The scale of the sector illustrates both its importance and the magnitude of the transition ahead. According to IIR, more than 5.4 billion refrigeration, air-conditioning and heat-pump systems are estimated to be in operation worldwide. The sector generates more than USD 300 billion in annual sales and employs approximately 12 million people. At the same time, refrigeration represents about 20% of global electricity consumption and contributes an estimated 7.5% of global CO₂ emissions, through the combined effects of energy use and refrigerant emissions. Looking at these figures, one may note why technological development in RACHP

can no longer be considered solely from an engineering perspective. Decisions concerning refrigerants, equipment efficiency, system architecture, standards, training, energy infrastructure and access to refrigeration increasingly interfere with climate policy, food security, health, industrial competitiveness and energy-system planning. In this context, one may raise the following question: should we be dealing with a purely technological challenge, or should we adopt a much broader and structured systems transition? The first option has shown that isolated actions and a narrow focus can lead to successive changes, each requiring additional effort to adapt. It is time to move from a finite mindset to an infinite mindset. The latter would adopt a broader approach which anticipates continuous change, builds long-term resilience and more importantly, recognises that no country or actor can address this transition alone. This is where international cooperation becomes essential. In many ways, international cooperation is already embedded in this sector. Our equipment, components, refrigerants and cold-chain systems are designed, manufactured, traded and operated across borders. The same applies to food and health supply chains that depend on these systems. In many respects, cooperation is already embedded in the way the sector functions. The next step now is to bring the same level of cooperation to the way we think, plan and make decisions: sharing evidence, aligning approaches, learning from different regional experiences and anticipating transitions together. This is how we can accelerate progress and avoid repeatedly reinventing solutions in isolation. The reader here should be careful not to confuse learning from one another with adopting a

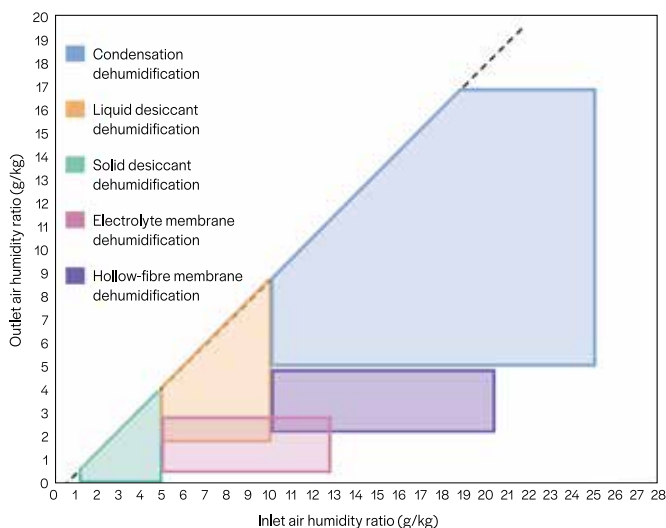


Figure 1: Inlet and outlet air humidity ratio ranges for various dehumidification technologies.

cookie-cutter approach. A technology that delivers substantial energy savings in one country may not perform in the same way elsewhere. Its performance depends on ambient temperatures, humidity, controls system, operating practices and importantly the skills available to install, commission, operate and maintain it. In addition, technology should not be promoted in isolation from the capacity required to support it. Training must come first, and it must be sustained over time so that local professionals can progressively build the expertise needed to operate, maintain and adapt these systems autonomously.

The perfect refrigerant doesn't exist; the perfect system design doesn't exist, the compromise? Yes. We may operate a system using a refrigerant with zero ODP and very low or even ultra-low GWP, but this has limited value if the system itself is inefficient. We should stop thinking that energy efficiency is only about selecting high efficient components. This also includes an appropriate system design to cope with extreme conditions. Even where the necessary skills and technology are available, systems must be properly commissioned and subsequently operated and maintained within the conditions and performance range for which they were designed. Otherwise, the expected efficiency gains may not be realised in practice. This takes me to conclude that achieving the sector transition would definitely require combination of efforts on reducing both direct (from refrigerant use) and indirect emissions (from energy use). I would go one step further: even a highly efficient system using a low-GWP refrigerant, may still have a significant climate impact if the electricity supply originates from a high carbon factor energy source. This is why refrigerant choice, system efficiency and the carbon intensity of the energy supply must be considered together. This is another dimension of the infinite mindeist, cited earlier in the text, that we should start adopting to achieve a real transition. Another aspect about the mindset transition. An excellent talk by Andy Pearson regarding Risks in refrigeration was delivered during the 17th edition of the

IIR Gustav Lorentzen conference on natural refrigerants in Hamilton, New Zealand (August 2026), has challenged the common understanding about the risks perception in our sector. While the common understanding often focuses on issues such as flammability and toxicity, Pearson presented a much broader, system-level perspective, looking beyond these immediate health and safety concerns to the wider implications of threats related to the supply chain, utility costs, employee relations, reputational damage, recruitment, retention, AI, cyber security, legislation, litigation and the economical aspect. More information will be soon available in the conference proceedings in FRIDOC. This broader perspective about the refrigeration sector gives international cooperation a different role, which IIR has secured for our sector more than a century ago. Its contribution is not limited to documenting scientific progress. By bringing together scientific expertise, engineering practice and policy considerations, the IIR provides an independent technical assessment which governments, industry, researchers and international organisations can use to evaluate technological options. The recent IIR publications considered in the following section illustrate this function particularly clearly.

The information provided below ranges from global modelling of air-conditioning emissions and assessments of heat-pump and dehumidification technologies to application-specific analyses of supermarkets, domestic appliances, fishing vessels, walk-in cold rooms and refrigerated transport. The joint IIR-UNEP OzonAction technology briefs about cold chain technologies in warm climates, published late 2025, further demonstrate how international scientific cooperation can translate the objectives of the Montreal Protocol and its Kigali Amendment into practical technological pathways adapted to different economic and climatic conditions. The central conclusion emerging from these recent publications is that the transformation of RACHP is no longer driven by a single technological substitution. The sector is moving

simultaneously towards lower-GWP and natural refrigerants, higher energy efficiency, greater electrification, variable-capacity operation, thermal energy storage, renewable-energy integration, heat recovery and increasingly sophisticated monitoring and control. The role of AI and Internet of things has become increasingly preeminent the last decade and offer great opportunities for control and predictions.

AIR CONDITIONING: ADDRESSING BOTH DIRECT AND INDIRECT EMISSIONS WITH LARGER PERSPECTIVES

Air conditioning is perhaps the clearest illustration of the need for a system-level approach. The IIR estimates that air conditioning already accounts for more than 12% of global electricity consumption and approximately 5% of energy-related CO₂ emissions. Of the emissions attributed to air conditioning, approximately 77% are indirect emissions associated with electricity consumption, while 23% result directly from refrigerant emissions during operation and at end of life.

In this work, the IIR model considers a scenario combining a significant acceleration in equipment efficiency with a rapid reduction in refrigerant impacts, which could reduce global air-conditioning emissions by around one third by 2050, despite an estimated 2.5 fold increase in the global stock of air-conditioning equipment. Yet this projected growth raises a broader and equally important question: are our electricity grids and energy infrastructures ready to accommodate such a rapid expansion in cooling demand? The transition cannot therefore be considered at equipment and refrigerant level alone; it must be accompanied by adequate grid capacity, greater system flexibility, renewable-energy integration, energy storage, and strategies to manage increasingly significant cooling related peak loads.

Technological development is consequently progressing at several levels. At equipment level, higher efficiency, low-GWP refrigerants and

improved refrigerant containment remain fundamental. At building level, passive measures such as improved design, solar shading, green roofs and phase-change materials can reduce the cooling load before mechanical cooling is required. At system level, district cooling can exploit economies of scale and potentially integrate natural heat sinks, renewable energy or waste-energy sources. Photovoltaic powered cooling is particularly relevant in regions where peak solar availability coincides with peak cooling demand. Personal or localised cooling concepts, including radiative systems, represent another direction by conditioning the occupied environment rather than cooling an entire space uniformly. The reader is directed to IIR publication on passive cooling technologies for further information. This evolution from equipment centred to a system centred approach is likely to be one of the defining characteristics of future air conditioning.

DEHUMIDIFICATION: SEPARATING TEMPERATURE AND MOISTURE CONTROL

A related development is the increasing recognition that temperature and humidity should not necessarily be controlled through the same thermodynamic process. This is especially important in tropical and subtropical climates, where latent loads may be very high. The IIR's 2026 technical brief on the topic, reports that dehumidification can account for more than half of HVAC energy demand, while HVAC itself may represent more than half of total building energy consumption in hot and humid regions. Humidity control is also critical in industrial applications including pharmaceutical production, electronics, lithium-battery manufacturing, food processing and optical manufacturing. Conventional condensation using vapour-compression refrigeration remains dominant, accounting for more than 70% of the dehumidification market, and VCR dehumidifiers can achieve electrical COP values of approximately 2.5-4.0.

Solid-desiccant systems are also commercially mature and are particularly suitable for deep dehumidification. Liquid-desiccant systems, assessed as proven technologies, provide the additional advantage of allowing temperature and humidity to be controlled more independently and are increasingly relevant to hospitals, large fresh-air systems and industrial processes. Membrane-based dehumidification remains at an earlier stage of commercialisation but offers potential for compact and highly localised moisture control. The likely development pathway is therefore not wholesale replacement of established technologies but their optimisation and combination. Hybridisation of vapour compression, solid or liquid desiccants and membrane technologies can match the process more closely to the required humidity level and available energy source. As it can be seen in Figure 1, solid desiccant dehumidification is particularly effective for deep dehumidification, whereas vapour-compression systems dehumidifiers offer high moisture-removal capacity under humid conditions. Regeneration of desiccants using heat pumps, waste heat or renewable thermal energy is particularly promising. A cited industrial application in Xiamen reported energy savings of 20–30% or more for a liquid-desiccant system relative to conventional vapour-compression air conditioning. Digitalisation is also entering this field: sensor-based control and artificial intelligence can dynamically regulate humidity and reduce unnecessary over-dehumidification.

DATA CENTRES: COOLING THE RAPIDLY EXPANDING DIGITAL INFRASTRUCTURE

The rapid expansion of data centres is creating a major new source of cooling demand. According to IIR, Global data centres consumed an estimated 240–340 TWh of electricity in 2022, around 1-1.3% of global electricity demand, with cooling accounting for about 40% of their energy use. It can be depicted from

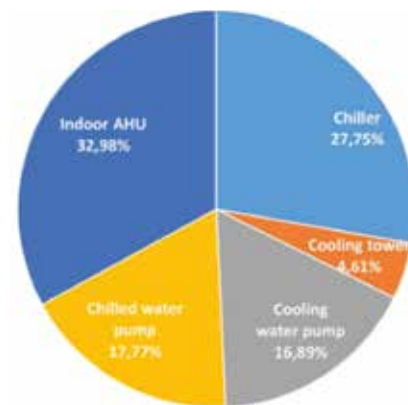


Figure 2: Breakdown of the consumption of cooling energy in a data centre

Figure 2, that the transmission and distribution stage plays a key role in improving energy efficiency and reducing emissions in data centres. Technological development is moving towards liquid cooling for high-density computing, together with natural and hybrid cooling, waste-heat recovery, and AI-based optimisation and digital twins. This application reinforces a broader challenge for the RACHP sector: cooling technologies cannot be considered independently from the energy system. As data centres, buildings and other cooling applications expand, greater attention will be needed to grid capacity, renewable-energy integration, heat recovery and intelligent energy management.

HEAT PUMPS: EXPANSION OF THE TEMPERATURE AND REFRIGERANT ENVELOPE

Heat pump development is occurring simultaneously at residential and industrial scales. In domestic applications, the transition towards natural refrigerants is already well advanced in parts of Europe. R290 is attracting particular interest because of its favourable thermodynamic and transport properties, very low climate impact and ability to achieve efficiencies comparable with or higher than many synthetic refrigerants. The main technical constraint remains flammability, making refrigerant charge reduction, leak prevention, elimination of ignition sources, ventilation and appropriate installation practices integral elements of system design.

Revised standards, including IEC 60335-2-40:2022 and EN 378, are perceived by some as technological enablers and as simply regulatory requirements, by others.

The market evidence indicates that the heating sector transition has moved beyond the demonstration phase. The IIR reports that R290 heat pumps already represented approximately 20% of the German domestic heat-pump market at the time of the assessment. Air-to-water heat pumps, particularly outdoor packaged units, are becoming a major alternative to gas boilers for space heating and domestic hot water. Current research is expected to concentrate on reducing refrigerant charge, improving flexibility and efficiency, and managing the refrigerant throughout the equipment life cycle. At the opposite end of the temperature range, high temperature heat pumps (HTHPs) are extending electrification into industrial process heat.

The 100-200°C range is of particular importance for food processing, chemicals, textiles, papermaking, brewing, plastics and metals. Recent systems demonstrate that heat pumps are no longer confined to low-temperature space heating: commercially available HTHPs now cover approximately 100-300°C and capacities extending to around 100 MW. Several thermodynamic architectures are developing in parallel. Vapour-compression systems remain the most widely deployed, with cascade cycles, multi-stage compression, vapour or liquid injection, new compressor concepts and alternative working fluids extending achievable supply temperatures beyond 200°C. Absorption systems can exploit industrial waste heat directly when suitable heat sources are available, while hybrid absorption-compression cycles offer another route to high temperatures while limiting operating pressures. Particularly important is the integration of heat pumps into the wider process rather than treating them as stand alone boiler replacements. Simultaneous heating and cooling, also referred to as thermal integration, can substantially improve

REFRIGERANTS FOR COMMERCIAL, PROFESSIONAL, AND DOMESTIC REFRIGERATION		
Types of refrigeration	Current higher GWP refrigerants (GWP ₁₀₀ kg-CO ₂)	Alternative lower GWP refrigerants (GWP ₁₀₀ kg-CO ₂)
Commercial	Centralised and integrated: HFC-134a (1530); HFC-404A (3920); HCFC-22 (1980)	Centralised: R-744 (1) Centralised and secondary loop: HC-290 (0.02), HC-1270 (1.8) Centralised and integrated: wide range of HFO and HFO blend refrigerants (R-454C, R-454A, R-455A)
Professional	HFC-404A (3920), HFC-134a (1530)	HC-290 (0.02), HC-600a (3), wide range of HFO and HFO blend refrigerants (R-454C, R-454A, R-455A)
Domestic	HFC-134a (1530)	HC-600a (3)

Figure 3: Commercial, professional and domestic refrigeration: Current high-GWP Vs. Alternative lower GWP

effective system performance, while thermal energy storage allows heat production to be shifted in time and aligned with electricity prices or renewable energy availability. The technology is already commercially credible and its technical feasibility is proved, although economics remain site-specific.

A brewery steam-supply example operating at 120°C and a COP of 1.85 achieved a reported 46% reduction in electricity consumption relative to an electric boiler, with a payback period of 2.4 years. The remaining barriers are increasingly associated with electricity-to-fuel price ratios, grid carbon intensity, investment cost and specialist skills. At temperatures above approximately 200°C, compressor reliability, lubrication and materials nevertheless remain active areas of research.

COMMERCIAL, PROFESSIONAL AND DOMESTIC REFRIGERATION: MATURE TECHNOLOGY UNDERGOING RAPID OPTIMISATION

The cold chain demonstrates how incremental improvements to mature vapour-compression technology can produce substantial system benefits. In supermarkets, professional kitchens and domestic refrigeration, technological development is concentrating on temperature stability, energy efficiency, refrigerant containment and low-GWP working fluids. In commercial refrigeration, temperature management remains a significant practical weakness. Field studies reviewed by the IIR-UNEP technology brief indicate that 7–35% of retail establishments assessed failed to maintain

appropriate refrigerated or frozen-food temperatures. Enclosed display cabinets generally maintain more uniform product temperatures than open cabinets. This apparently simple design change can therefore improve food safety while reducing infiltration loads and energy consumption. Supermarket refrigeration is particularly important because it frequently accounts for 40–60% of store electricity consumption. Technologies being deployed or evaluated include doors and efficient lighting on medium-temperature cabinets, improved evaporator configurations, parallel compression, CO₂ systems with heat recovery, and integration of renewable electricity with thermal storage.

The refrigerant transition is also increasingly visible. Food service cabinets have moved from R134a towards R290, facilitated by revisions to IEC 60335-2-89 that increased permissible A3 refrigerant charges from 150 g to 500 g for relevant equipment. Supermarkets are progressively adopting R744, R290 and lower-GWP blends, while around 75% of newly sold domestic refrigerators reported in the source assessment were already using R600a. The Figure 3 lists current high-GWP Vs alternative low-GWP refrigerants for commercial, professional and domestic refrigeration. Beyond conventional vapour compression, the same technology brief identifies solid-state refrigeration as an important longer-term research frontier. Magnetocaloric, electrocaloric, mechanocaloric, ionocaloric and multicaloric systems, together with thermoelectric, spintronic, radiative and laser-cooling approaches, are



Figure 4: Eutectic solutions: (A) full electric last-mile delivery light vehicle; (B) multi-temperature transport in a van; (C) full electric.

being explored for applications ranging from compact refrigeration and electronic thermal management to high temperature heat pumping and cryogenic cooling. Their attraction lies in the possibility of compact and low-noise systems, the absence of conventional fluid refrigerant leakage in caloric devices, and access to temperature ranges or scales that can be difficult for vapour compression. Most remain far from broad commercial deployment because performance, material cost, manufacturability and scalability still require substantial research, which IIR is supporting, particularly through the IIR Thermag conference series on solid-state cooling, heating and energy harvesting.

WALK-IN COLD ROOMS: TECHNOLOGY ADAPTED TO ENERGY ACCESS AND FOOD-SYSTEM NEEDS

Walk-in cold rooms (WICR) illustrate another dimension of technological development: innovation must be judged not only by thermodynamic performance but by accessibility, reliability and compatibility with the surrounding food system. In many Article 5 countries, standard electrically driven direct-expansion systems remain the principal technology, generally using compact monobloc or split units. Increasingly, these systems are being combined with solar photovoltaics and thermal energy storage to operate where grid supply is unreliable or absent. Thermal storage can range from simple water containers to ice banks and phase change material panels. It reduces peak cooling capacity as mentioned earlier, provides resilience during power interruptions which represents a major issue in many developing countries, mainly

during extreme heat conditions, and can reduce the size of electrical battery storage required in solar-powered installations. As for buildings, passive measures can also be valuable for this application: shading and evaporative pre-cooling may lower product temperatures by approximately 5-15°C below ambient before mechanical refrigeration is applied. The reader is directed to IIR publication on evaporative cooling technologies for more information. The refrigerant transition is technically achievable in WICR. Virtually all suppliers assessed in the brief offer low- or ultra-low-GWP options using R290 or R600a, and many monobloc units operate with approximately 150g of propane. Life cycle analysis of a solar-powered WICR showed the importance of looking beyond operational electricity alone: manufacturing accounted for more than four fifths of the life cycle impact in the example studied, whereas the use phase represented less than 2% because of solar electricity. Replacing an HFC with a hydrocarbon refrigerant reduced refrigerant related life cycle GHG emissions by approximately 99% in the comparison presented. Beyond electricity-driven systems, emerging autonomous refrigeration technologies also illustrate how cooling can be decoupled from continuous electrical supply. One innovative approach is based on a reversible chemical sorption process between a reactive salt and ammonia (R717), as natural refrigerant with zero GWP. The process is simple, thermal energy is stored in chemical form and converted into cooling on demand. The system can be driven by low-temperature heat sources, including solar thermal energy and recovered waste heat, thereby reducing

reliance on electricity and providing flexible and resilient cooling. Such technology developed by the French company Sofrigam is particularly relevant to remote or weak-grid areas exposed to hot climates and can be applied to autonomous walk-in cold rooms for post-harvest preservation, vaccine storage and decentralised food and pharmaceutical cold chains. The same principle can also support refrigerated transport and cold-chain logistics by providing autonomous cooling for temperature-sensitive products during transportation and distribution. These developments point towards a broader role for renewable-heat-driven refrigeration alongside photovoltaic-powered conventional systems, particularly where reliable electricity supply cannot be guaranteed. The principal obstacles are increasingly economic and institutional. Solar WICRs are expanding. More than 1,400 units were reported in India by February 2025, while installations are also growing in Africa, but smallholder affordability remains difficult. Cooling-as-a-service, shared cold rooms, rental models and integration into complete farm-to-market cold chains are therefore as important as equipment innovation. For larger deployment, technical performance standards, independent testing, reparability and training in the safe use of hydrocarbon refrigerants are essential. More details can be found in the UNEP-IIR brief.

REFRIGERATED ROAD TRANSPORT IN HOT CLIMATES: ELECTRIFICATION, STORAGE AND NATURAL REFRIGERANTS

Refrigerated transport faces a different set of boundary conditions: vibration, limited space and weight, frequent door opening, changing engine speeds and high ambient temperatures. The IIR estimated a global refrigerated road fleet of approximately 5.7 million vehicles in 2024, with substantial expansion expected as cold-chain coverage increases, particularly in the Global South. All information below is originated from the same reference. Improving insulation is the first

technological lever because every reduction in thermal load reduces both required capacity and operating energy. Reinforced insulation has been shown to reduce thermal loads by approximately 22% in long distance applications under southern European conditions.

Vacuum-insulated panels can provide exceptionally low thermal conductivity but still face cost, manufacturing and repair constraints. Door infiltration is equally important for distribution vehicles: experiments under hot conditions found that appropriately designed air curtains could reduce infiltration loads substantially.

The refrigeration unit itself is increasingly being decoupled from the vehicle engine. Conventional mechanically driven compressors operate at speeds determined by vehicle operation rather than cooling demand.

Electrification enables variable-speed compressors, batteries, photovoltaics and regenerative e-axes. In one door-to-door delivery analysis, separating refrigeration from the driveline and regulating compressor speed according to cooling demand reduced refrigeration energy use by 26%. Cold thermal energy storage offers another route, particularly for short distance distribution. Eutectic plates (see Figure 4) and other phase change systems can be charged at a depot, shifting refrigeration equipment away from the vehicle and simplifying maintenance. Natural refrigerants are also progressing. R290 systems tested at ambient temperatures up to 50°C achieved COP improvements of 15-25% for medium temperature operation and 10-30% for low-temperature operation compared with R404A in the studies reviewed, together with reductions in diesel use and emissions. CO₂ transport refrigeration is less mature in very hot climates because of space, mass and heat-rejection constraints, but modelling of a developing CO₂ unit indicated a seasonal COP 27% higher than an R134a reference and a 32% reduction in overall life-cycle emissions. Renewable integration is also increasingly practical. Photovoltaics installed

on refrigerated vehicles have demonstrated the potential to cover more than 40% of refrigeration energy demand in some semi-trailer applications, while studies of last-mile delivery under Athens climatic conditions found annual solar production equivalent to 65-112% of refrigeration requirements, depending on configuration. As for the other applications, IoT and AI-based logistics optimisation provide an additional efficiency layer by improving routing, temperature transparency and operational decisions.

FISHING VESSELS: REFRIGERATION TECHNOLOGY UNDER DEMANDING MARINE CONSTRAINTS

Refrigeration on fishing vessels is technologically diverse, ranging from shore produced ice on small artisanal craft to refrigerated seawater (RSW), plate freezers, blast freezers, ice slurry systems and complete processing plants on industrial vessels.

This diversity is important because small-scale vessels represent approximately 89% of the global fishing fleet, and access to adequate onboard chilling remains highly uneven. For large catches, RSW systems cool seawater to approximately -1.5 to +0.5°C. Ammonia remains highly efficient for large-capacity systems, while compact CO₂ systems are gaining interest where space and safety considerations favour them. In warm waters, ammonia remains particularly attractive for RSW duty, whereas R717/R744 cascade systems can combine efficient heat rejection with CO₂ stages capable of reaching around -50°C for deep freezing. Innovation is also happening at smaller scale.

An R290 flake-ice system under development for Indian fishing vessels was modelled at 30 kW capacity with a COP of 1.76 at an evaporation temperature of -25°C and condensation temperature of +40°C, demonstrating the potential for propane even under demanding tropical conditions. Heat-driven

absorption systems offer the theoretical possibility of exploiting engine waste heat but remain constrained on smaller vessels by weight, volume, complexity and insufficient recoverable heat.

Marine refrigeration is also becoming digital. Integration of refrigeration data with vessel monitoring systems, automation systems, weather information and catch records creates opportunities for predictive maintenance, better system sizing and optimisation of fishing routes. In parallel, electrified or hybrid propulsion, thermal storage and waste-heat recovery are creating opportunities to integrate previously separate heating, cooling and propulsion systems.

Refrigerant containment is particularly important at sea because vibration and mechanical movement make low leakage rates difficult to maintain. The reviewed data indicate continued use of R22 in parts of the global fleet and significant refrigerant losses. The transition towards ammonia, CO₂ and hydrocarbons therefore has both climate and operational significance, but it must be accompanied by appropriate materials, leak detection, ventilation, risk assessment and crew training.

AN OUTLOOK

The direction of RACHP travel is increasingly clear. The future RACHP system should be more efficient, more integrated with the energy system, less dependent on high-GWP working fluids and more responsive to real operating conditions. It will also need to be adapted much more carefully to climate, application and local capacity. Achieving this transition at global scale requires continued scientific progress, but equally requires the international exchange of evidence, harmonised approaches to safety and performance, investment in skills, and sustained cooperation between governments, research organisations and industry and this is precisely where international organisations such as the IIR have their greatest value.

Kigali Era Gateway to Climate Friendly Cooling Under the Montreal Protocol



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This paper presents the latest successes of the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol), driven by the 2016 Kigali Hydrofluorocarbon (HFC) Phase Down Amendment and the complementary 2016 Kigali Energy Efficiency Decision XXVIII/3. The information in this paper is based on our forthcoming book: *Protecting the Ozone Layer & Climate: Kigali Energy Efficiency Triumph*, published in partnership with the Climate and Clean Air Coalition (CCAC), the Montreal Protocol Ozone Secretariat, and the Institute for Governance & Sustainable Development.

This essay highlights the importance of leadership by corporations, governments, and citizens in avoiding climate tipping points while minimizing the accumulation of trifluoroacetic acid (TFA) from HFC and hydrofluoroolefin (HFO) refrigerants, and by avoiding the formation of hazardous volatile organic compounds (VOCs) from hydrocarbon refrigerants.

It presents a blueprint for the way forward on unfinished business, including lifecycle refrigerant management (LRM), access to the best available technology, and manufacturers' graceful withdrawal from hazardous fluorocarbons as soon as they are no longer needed.

KIGALI ERA (2009-2026) SUCCESSSES OF THE MONTREAL PROTOCOL

We define the "Kigali Era" as the period between the 2009 science warning by Velders et al. and the 2026 10th Anniversary of the Kigali Amendment and Kigali Decision that has repurposed the Montreal Protocol ozone treaty to ambitiously protect climate.

The metric for climate friendly cooling is life cycle climate performance (LCCP) taking into account direct refrigerant greenhouse gas (GHG) emissions, indirect carbon-equivalent energy emissions, and embodied GHG emissions from equipment manufacture, marketing, servicing and recycle at end of product lifetime. Added to that are the non-climate concerns of atmospheric fate, safety, and toxicity.

➤ The ozone layer is the only Planetary Boundary breached and then recovered from the danger zone, offering hope for a sustainable Earth!

➤ 2026 is the last Replenishment of the Multilateral Fund for the Implementation of the Montreal Protocol (MLF) for ozone-depleting substance (ODS) phaseout—the next Replenishment will be for HFC phase-down and energy efficiency!

➤ MLF Executive Committee Decisions opened US \$20 million, US \$40 million, and US \$100 million energy-efficiency funding windows!

➤ The Africa Group campaign calling for access to best available cooling technology and importer-exporter cooperation to stop the dumping of inefficient cooling equipment is reflected in Montreal Protocol Decision (XXXV/13) and the Preamble to the EU F-Gas Regulation 2024/573! This campaign is inspiring other countries to demand access to energy efficient appliances without obsolete ODS and HFC refrigerants.

➤ Manufacturers of energy-efficient room air conditioners (RACs) are penetrating global markets. For example, in Ghana, efficient inverter R-32 and R-290 models are increasingly offered; both refrigerants have no atmospheric degradation to TFA! Brands that now offer R-290 models in Ghana are Hisense, Midea, and GREE. Brands that now offer R-32 models in Ghana include

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Amcon, Chigo, Gree, Haier, Hilbery, Hisense, Innova, MDV, Midea, SPS, TCL, and H&A.

➤ Leadership by Japan has advanced LRM in the Montreal Protocol, including as reflected in Japan's co-chairmanship of the CCAC Cooling Hub and the recently published National Action Plans for Lifecycle Refrigerant Management: A Practical Guide for Developing Countries!

➤ The "Accra-Helsinki Group on Sustainable Cooling," which evolved from the legacies of the Montreal Protocol "Toronto Group" and the "Stockholm Group," is the new, informal incubator for ambitious ideas outside the formal plenary and contact group meetings, for fast action to strengthen the Montreal Protocol.

➤ Breakthrough cooling technology including rapidly expanding the safe use of natural hydrocarbon refrigerants in stand-alone refrigeration, room and portable air conditioners, and in secondary-loop heat pumps for all-electric vehicles.

➤ Breakthrough R-32 cooling technology achieving lowest carbon footprint in high ambient temperature by superior energy efficiency, larger safe refrigerant charge, and leak tight design and service.

➤ Greater energy efficiency driven by minimum national and voluntary energy performance standards enhanced by the rapid implementation of clean wind and solar energy and occupant spaces designed for reduced cooling and heating demands!

➤ Parties and national authorities are considering policy responses to newly published science in the journal *Nature* warning that feedstock emissions will delay mid-latitude ozone recovery by 7 (6-11) years and earlier published policy analysis in the *Proceedings of the National Academy of Sciences (PNAS)* providing options for narrowing the feedstock exemptions under the Montreal Protocol, while also documenting that ODS and HFC are used as plastic feedstocks, contaminating workplaces and communities and contributing downstream to the contamination of fresh water, land, oceans, and atmosphere, and providing options for upstream controls under the Montreal Protocol.

Indicative List of Non-Governmental Organizations Supporting Adoption and Implementation of the Kigali Amendment

Air Conditioning Contractors of America (ACCA)
Air-Conditioning, Heating, and Refrigeration Institute (AHRI)
Alliance for Responsible Atmospheric Policy (ARAP)
American Chemistry Council (ACC)
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)
Basel Agency for Sustainable Energy (BASE)
Brazilian Refrigeration, Air Conditioning and Ventilation Industry Association (ABRAVA)
Business Roundtable
Center for Climate and Energy Solutions (C2ES)
Center for Shared Responsibility and Technology Ambition (CSRTA)
Centro Studi Galileo (CSG) - Industria & Formazione
Climate Action Network (CAN) International
Climate and Clean Air Coalition (CCAC)
Council on Energy, Environment, and Water (CEEW)
Environmental Defense Fund (EDF)
Environmental Investigation Agency (EIA) (USA and UK)
European Partnership for Energy and the Environment (EPEE)
Greenpeace International
Industrial Technology Research Institute (ITRI)
Institute for Governance & Sustainable Development (IGSD)
Instituto Clima e Sociedade (ICS)
International Institute of Refrigeration (IIR)
Japan Electrical Manufacturers' Association (JEMA)
Japan Refrigeration and Air Conditioning Industry Association (JRAIA)
Korea Refrigeration Air-Conditioning Industry Association (KRAIA)
Latin America and Caribbean Network for Sustainable Cooling (LAC Cool)
National Association of Manufacturers (NAM)
Natural Resources Defense Council (NRDC)
Sustainable Energy for All (SE for All)
Semiconductor Industry Association (SIA)
United States Chamber of Commerce (USCC)
World Resources Institute (WRI)

Table 1: Indicative List of NGOs supporting adoption and implementation of the Kigali Amendment

The success of the Montreal Protocol in sustainable cooling is from the many industry and public interest organizations working together to transition away from inefficient cooling products with obsolete refrigerants, particularly in the developing world. They work to remove barriers and implement standards in support of environmentally superior HFC replacements, and promote professional installation and service,

including LRM and local cement kiln destruction of surplus ODSs and HFCs consistent with Montreal Protocol decisions.

Table 1 presents an indicative list of public-interest and industry non-governmental organizations (NGOs) that supported the adoption of the Kigali Amendment. Table 2 is a summary of seven eras of cooling since the industrial revolution beginning in about 1800.

The Seven Historic Eras of Cooling and the Likely Eighth Era

- 1) Primitive refrigeration (root cellars, spring houses, local winter ice used in hotter months, evaporating water, and handheld fans)
- 2) Point-of-use manufactured ice using toxic and flammable refrigerants
- 3) Distributed mechanical refrigeration, still using toxic and flammable refrigerants
- 4) Odourless, colourless, non-flammable, non-toxic, energy efficient, and affordable CFCs that are ozone-depleting greenhouse gases
- 5) Ozone-safe, flammable and toxic, low-GWP natural refrigerants (ammonia, CO₂, and hydrocarbons) plus ozone-safe, non-flammable, non-toxic HFC greenhouse gases (some degrading to hazardous TFA)
- 6) Expanded use of natural refrigerants plus non-flammable, non-toxic, low-GWP HFOs (most degrading to hazardous TFA)
- 7) Expanded use of natural refrigerants plus TFA-free HFCs and HFOs; all in leak-tight systems with LRM, including destruction at the end of useful life
- 8) The next "Moonshot" cooling era might be solid state cooling, including barocaloric, elastocaloric, magnetocaloric, and thermoelectric (no doubt with advanced building placement and orientation, design, insulation, landscaping, and water features, reflectivity, shading, thermosiphoning, etc.)

Table 2: The Seven Historic Eras of Cooling and the Likely Eighth Era

THE CONTINUING SAGA OF REFRIGERANTS WITH UNANTICIPATED CONSEQUENCES

Storage of perishable food was first accomplished by canning, drying, fermenting, pickling, salting, smoking, sterilization, sulfurating, and sugaring. Refrigeration and air conditioning began with natural technology such as shading, root cellars, spring houses, water evaporation, and hand-held fans.

Cooling evolved in cold climates to use winter ice stored for summer use, and then to global trade in ice to markets without annual freezing temperatures.

When natural ice sources were bilocally and chemically contaminated emerging motive power was used to make ice from clean local sources with flammable and toxic refrigerants such as ammonia (NH₃), carbon dioxide (CO₂), ethers, hydrocarbons, sulphur dioxide (SO₂), and methyl chloride (CH₃Cl). With the invention of electricity generation, companies abandoned ice as a transportable cold ballast and concentrated on point-of-use cooling equipment located in businesses and homes but still using flammable and toxic

refrigerants.

Before 1930, mechanized cooling equipment used flammable and toxic refrigerants that maimed and killed humans and destroyed property. In 1930, a joint venture of General Motors and DuPont began marketing chlorofluorocarbons (CFCs) that are non-flammable, non-toxic, colourless, odourless, energy efficient, and affordable.

Until 1974 it was not appreciated that CFCs deplete stratospheric ozone that shields Earth against harmful ultraviolet radiation and until 1975 it was not appreciated that CFCs are powerful greenhouse gases (GHGs). Likewise, when HFCs first replaced CFCs, it was not appreciated that economic growth in Article 5 markets coupled with global inaction on carbon dioxide from fossil fuel would make high global warming potential (GWP) refrigerants unsustainable.

And until the about 1990, it was not appreciated that many HFCs and HFOs atmospherically decompose to TFA. Similarly, it is not yet appreciated that hydrocarbon refrigerants are unsustainable unless responsibly supplied from non-fossil fuel sources or where otherwise emitted and should be in leak tight equipment serviced with recovery and reuse or

destruction to mitigate VOC damage to health and ecosystems.

In 1985, British scientists warned of a seasonal Antarctic ozone hole the size of Texas and in 1987 the Montreal Protocol was agreed as a Start and Strengthen treaty that started with just a 50% reduction in a short list of CFCs and a freeze in halon and was strengthened to almost 100 ozone-depleting substances (ODSs) that are now 99+% phased out worldwide from production and consumption.

A COMMON-SENSE WAY FORWARD ON TFA

TFA accumulation is an unanticipated consequence of saving the ozone layer by the rapid replacement of 15% of ODSs with HFCs and HFOs, while 85% was replaced with not-in-kind solutions. The Montreal Protocol dilemma is that without a rapid HFC phasedown or phaseout, carbon-equivalent climate forcing may exceed climate tipping points that could end life on Earth until recovery over geologic time. The technical reality is that not all HFCs and HFOs can be replaced in the immediate future.

One common-sense way forward to minimize and mitigate TFA and VOCs while avoiding climate tipping points is to:

- Restrict domestic sales and export the use of any HFC or HFO that degrades to TFA when energy efficient alternatives with superior life cycle climate performance (LCCP) are available that satisfy critical environmental, health, and safety criteria,
- MLF to incentivize A5 Parties leapfrogging TFA refrigerants, and to avoid refrigerants that degrade to TFA
- Collect and destroy ODS and HFC banks with TFA trading and offsets as financial bonus for destruction avoiding TFA
- Early replacement of installed cooling equipment that was inefficient when purchased and improperly installed and serviced for energy efficiency with financial bonus for destruction avoiding TFA
- Find synergy with accelerated transition to all-electric vehicles using R-290 SL-heat pumps.

The Illegal Trade in Substances Controlled by the Montreal Protocol



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New challenges under the Kigali Amendment and opportunities to strengthen global implementation

ABSTRACT

The Kigali Amendment brings multiple new challenges, in particular for Article 5 countries that are simultaneously phasing out HCFCs. Experience from the phase-out of ozone-depleting substances (ODS) and Europe's early action to phase out hydrofluorocarbons (HFCs), shows that as the phase-down progresses, robust policy measures will be needed to avoid large-scale illegal trade.

Since 2019, the Parties to the Montreal Protocol have held multiple discussions on 'Further strengthening Montreal Protocol institutions', most recently through an informal meeting on facilitating implementation of the Montreal Protocol ahead of the 37th Meeting of the Parties (MOP37). This paper discusses lessons from the illegal trade of HFCs in the EU, exploring a range of opportunities to advance a series of concrete actions to strengthen the effective implementation and enforcement of the Montreal Protocol.

INTRODUCTION

The Montreal Protocol is widely regarded as one of the world's most successful environmental agreements. Since its adoption in 1987, it has driven the global phase-out of ozone-depleting substances (ODS), delivering major benefits for both the ozone layer and the climate. The 2016 Kigali Amendment expanded its remit to include hydrofluorocarbons (HFCs), which commits the world's nations to significantly reduce consumption and production of HFCs.

As the Kigali Amendment enters

early phases of implementation for Article 5 Parties, many face the dual challenge of completing the hydrochlorofluorocarbon (HCFC) phase-out while beginning to reduce HFC consumption. Experience from previous ODS phase-outs demonstrates that tightening supply controls, while environmentally essential, also creates strong financial incentives for illegal trade if regulatory systems and enforcement fail to keep pace. Europe provides an important case study. As the first region to introduce an HFC phase-down, it experienced widespread illegal trade within only a few years of implementation, prompting the introduction of some of the world's most comprehensive measures to strengthen enforcement.

However, Europe's experience also demonstrates that enforcement alone cannot solve the problem. Illegal trade is ultimately driven by continued demand for controlled substances. Where industries remain dependent on HFCs, criminal networks are presented with lucrative opportunities to supply cheaper illegal products. Conversely, where policies accelerate the uptake of non-fluorinated alternatives, demand for illegal HFCs falls.

LESSONS FROM PREVIOUS ODS PHASE-OUTS

Illegal trade has accompanied every major phase-out under the Montreal Protocol.

During the 1990s, as developed countries rapidly phased out chlorofluorocarbons (CFCs), differences in production and consumption controls created opportunities for criminal networks to exploit price disparities between regulated and unregulated markets. EIA investigations uncovered

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Figure 1: Flow chart showing how criminals capitalise on ongoing HFC demand and surging prices, undermining compliance and leading to additional emissions.

Chinese exporters falsely declaring virgin CFCs as recycled refrigerants, while US authorities exposed transit regimes being used to divert illegal shipments onto domestic markets. These experiences prompted Parties to adopt an Amendment to the Protocol, introducing mandatory import and export licensing systems that remain a cornerstone of the Protocol today.

Similar patterns emerged during the hydrochlorofluorocarbon (HCFC) phase-out. In Europe, UNEP estimated that up to ten shipments of illegal HCFCs entered southern Europe each day during the late 2000s. Elsewhere, customs authorities in the Philippines and Thailand intercepted cylinders falsely labelled as HFC-134a that were found to contain mixtures of CFCs, HCFCs and hydrocarbons. These cases demonstrated that illegal traders rapidly adapt to new controls, exploiting weaknesses in licensing systems, customs procedures and product identification.

Many of the methods first observed during ODS phase-outs continue to characterise illegal HFC trade today. These include false labelling, misdeclaration of customs codes, diversion of goods under transit procedures, fraudulent claims that

virgin refrigerants are recycled or reclaimed, and the concealment of cylinders within legitimate cargo. As HFC controls tighten under the Kigali Amendment, these well-established trafficking methods are likely to remain attractive unless Parties strengthen both enforcement and regulatory oversight.

The European Union (EU) provides the first large-scale example of these challenges under an HFC phase-down. Since introducing its quota system in 2015, the EU has experienced significant illegal trade, providing valuable lessons for countries now implementing the Kigali Amendment.

EUROPE'S EXPERIENCE WITH ILLEGAL HFC TRADE

The EU became the first major jurisdiction to phase down HFC consumption when it introduced a quota system under the 2014 F-gas Regulation. Despite significant stockpiling before the Regulation entered into force, reports of illegal imports began emerging within a year. In 2019, EIA's Doors Wide Open investigation demonstrated how easily HFCs could enter the EU without quota, and subsequent analysis suggested illegal imports

accounted for as much as 20–30 per cent of the European market during the early years of the phase-down. The economic incentives driving this trade are clear. Between 2014 and 2025, HFC prices within the EU increased by almost tenfold as quotas tightened. This created a substantial price differential between Europe and regions where HFC production remained unrestricted, allowing smugglers to generate significant profits even when selling refrigerants below legitimate market prices.

The trade has been particularly pronounced for very high global warming potential (GWP) refrigerants such as R404A. Because the EU quota is based on carbon dioxide equivalence (CO₂e) emissions, these gases consume a disproportionate share of available quota, making them increasingly expensive and difficult to obtain legally. While legitimate suppliers have gradually withdrawn from the market, illegal traders have met the continued demand. EIA investigations found traders openly offering banned refrigerants, while others marketed supposedly reclaimed gases that were suspected to be virgin imports.

At the same time, counterfeit refrigerants have become increasingly common, with high-GWP gases being falsely sold as newer, lower-GWP blends.

Recognising these challenges, the EU significantly strengthened its regulatory framework in 2024. The revised F-Gas Regulation goes beyond simply reducing HFC supply by introducing measures designed to close many of the loopholes exploited during the first phase of implementation. Among the most important innovations is the integration of the EU Customs Single Window on ODS and F-Gases, enabling customs authorities to verify real-time import quotas electronically before consignments enter the European market.

The Regulation also requires Member States to designate specialist customs offices, strengthens penalties for illegal trade, tightens eligibility requirements for new quota

applicants and introduces stricter controls on refillable cylinders and take-back schemes. Together, these measures represent one of the world's most comprehensive regulatory responses to illegal HFC trade.

However, Europe's experience also demonstrates that stronger enforcement alone is insufficient. Illegal trade persists because substantial demand for HFCs remains.

Commercial refrigeration illustrates this challenge particularly well. Although the EU prohibited many new supermarket refrigeration systems using high-GWP refrigerants from 2022, existing systems can remain in operation for 10 to 20 years. As a result, only around 34 per cent of centralised supermarket refrigeration systems had transitioned to natural refrigerants by 2025, leaving a large installed base dependent on HFC servicing. This continuing demand provides an attractive market for illegal imports.

The EU's experience therefore highlights the importance of introducing demand-reduction measures early in the phase-down. Equipment bans, subsidies and policies promoting natural refrigerants reduce future dependence on controlled substances and, consequently, the profitability of illegal trade. Waiting until shortages emerge before encouraging alternatives risks locking countries into prolonged demand for increasingly scarce refrigerants.

Another emerging challenge is the rapid growth of online marketplaces. Digital platforms have transformed the way refrigerants are traded, providing sellers with direct access to large numbers of customers while making regulatory oversight more difficult. A 2026 EIA assessment of HFC advertisements on Poland's Facebook Marketplace found widespread non-compliance with both the EU Digital Services Act and the F-gas Regulation.

Many advertisements lacked basic trader information, offered prohibited disposable cylinders or appeared to

disguise illegal products through misleading descriptions and images. As refrigerant sales increasingly move online, effective enforcement will require much closer engagement with digital platforms alongside traditional customs inspections.

Financial investigations also represent an underused enforcement tool. Illegal HFC trade frequently involves organised criminal networks engaged not only in smuggling but also in VAT fraud, customs evasion and money laundering.

EIA estimates suggest illegal HFC imports between 2018 and 2020 may have deprived European governments of around €77 million annually in unpaid taxes and customs duties. Recent prosecutions in Romania and Spain demonstrate that investigating financial crime alongside environmental offences can substantially strengthen enforcement outcomes and increase deterrence.

Taken together, Europe's experience demonstrates that successful implementation of the Kigali Amendment requires a balanced approach. Effective licensing systems, stronger customs controls and meaningful penalties remain essential, but they must be complemented by policies that reduce dependence on HFCs. Ultimately, enforcement can only limit illegal supply; lasting success depends on reducing the demand that makes illegal trade profitable in the first place.

WHAT THE KIGALI AMENDMENT CAN LEARN FROM EUROPE

As all countries begin implementing the Kigali Amendment, Europe's experience offers valuable lessons for strengthening the Montreal Protocol before illegal HFC trade becomes entrenched.

Discussions among Parties ahead of the 37th Meeting of the Parties (MOP37) highlighted many of these priorities, including stronger licensing systems, better information sharing, improved customs cooperation and enhanced monitoring of domestic HFC markets. These discussions

reflect growing recognition that implementation of the Kigali Amendment will require more than simply allocating quotas; it will need coordinated systems capable of preventing and detecting illegal trade throughout the supply chain.

One of the clearest lessons is the importance of introducing robust regulatory measures early. Europe demonstrates that waiting until quota reductions begin to constrain supply allows demand for HFCs to persist, creating profitable opportunities for criminal networks. Kigali Implementation Plans (KIPs) therefore provide a critical opportunity for Article 5 Parties to introduce targeted equipment restrictions in sectors where non-fluorinated alternatives are already commercially available, such as domestic refrigeration, commercial refrigeration and, increasingly, air conditioning. Reducing demand before supply shortages emerge is likely to be far more effective than relying solely on enforcement once illegal markets have become established.

The European experience also highlights opportunities to strengthen implementation mechanisms under the Montreal Protocol. Digital licensing systems that enable customs authorities to verify import authorisations in real time should become the norm, while closer integration between national ozone units and customs agencies would improve risk profiling and intelligence-led inspections.

Similarly, greater consistency in reporting, investigation procedures and penalties would make it harder for criminal networks to exploit differences between national regulatory systems. Expanding and formalising tools such as the Informal Prior Informed Consent (iPIC) mechanism could further strengthen international cooperation by allowing authorities to verify traders and shipments before goods cross borders.

Europe's experience also suggests that greater attention should be paid to areas that have traditionally received less focus under the Montreal Protocol.

Online marketplaces are becoming increasingly important channels for refrigerant sales and should be incorporated into national enforcement strategies.

Likewise, financial investigations should become a routine component of enforcement activity. Illegal HFC trade is often accompanied by tax evasion, customs fraud and money laundering, meaning that financial investigations can often impose penalties that are far more disruptive to organised criminal networks than environmental offences alone.

Finally, Parties should recognise that supply chain transparency will become increasingly important as HFC controls tighten. In many countries, proof of quota compliance is only required at the point of import, making illegally imported refrigerants difficult to distinguish from legitimate products once they enter domestic markets.

Strengthening digital record-keeping and, ultimately, introducing traceability systems that follow refrigerants throughout the supply chain would significantly reduce opportunities for illegal products to be laundered into legitimate distribution networks.

Similar approaches are already becoming standard practice in

sectors ranging from food production to pharmaceuticals and should increasingly be considered for controlled refrigerants.

CONCLUSION

Nearly four decades after the adoption of the Montreal Protocol, illegal trade continues to evolve alongside each successive phase-out. The transition from ozone-depleting substances to HFCs has not fundamentally changed the incentives that drive criminal activity; rather, it has created new opportunities for organised networks to exploit differences in regulation, enforcement and market demand. Europe's experience demonstrates that strong enforcement is essential but cannot succeed in isolation. Even the world's most comprehensive regulatory framework has struggled where demand for HFCs remains high.

As the EU approaches its next major quota reduction in 2027, continued dependence on HFC-based equipment is likely to increase pressure on legal supply chains and further strengthen incentives for illegal imports.

The most important lesson for Parties implementing the Kigali Amendment

is therefore that preventing illegal trade begins long before refrigerants reach the border. Effective customs controls, digital licensing systems, meaningful penalties and international cooperation are all critical components of a successful enforcement strategy.

However, these measures must be accompanied by policies that accelerate the transition to non-fluorinated alternatives and reduce long-term dependence on HFCs. Without sustained demand reduction, enforcement efforts will remain reactive rather than preventative.

The Montreal Protocol has repeatedly demonstrated its ability to evolve in response to new environmental challenges. By applying the lessons emerging from Europe's HFC phase-down; strengthening implementation institutions, improving international cooperation and accelerating the adoption of sustainable cooling technologies, Parties have an opportunity to prevent illegal HFC trade from reaching the scale previously seen during ODS phase-outs. Acting now will not only protect the integrity of the Kigali Amendment but also strengthen the Protocol's reputation as the world's most effective environmental treaty.



ATF – Associazione dei Tecnici Italiani del Freddo hosted in Casale Monferrato an international delegation of 11 trainers, all women, from the RAC sector in Asia, as part of a UNEP-promoted Train-the-Trainers programme dedicated to good practices in refrigeration and air conditioning, F-Gas management and the safe use of natural refrigerants.

Advancing Circular Refrigerant Management in Japan: Enhancing Recovery, Reclamation, and Digital Cylinder Tracking



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INTRODUCTION: GLOBAL TRENDS IN FLUOROCARBON MANAGEMENT AND JAPAN'S POSITION

Fluorocarbons (CFCs, HCFCs, HFCs, and HFOs) have long been used in a wide range of applications, including refrigeration and air conditioning equipment, insulation foams, and fire extinguishing agents. CFCs and HCFCs have been completely phased out under the Montreal Protocol, and the Kigali Amendment adopted in 2016 mandates the gradual reduction of HFC consumption. As a result, fluorocarbons are positioned as substances that must be managed for both ozone layer protection and climate change mitigation.

In Japan, the Fluorocarbon Emission Control Law requires emission reductions across the entire lifecycle—manufacturing, use, and disposal. However, challenges remain, including stagnant recovery rates at disposal and uncertainties related to emissions from insulation foams. Japan is a leading country in HFC reduction and has advanced institutional frameworks for recovery and reclamation. Nevertheless, emissions from insulation foams and cylinder management remain common challenges globally. This paper reviews Japan's fluorocarbon material flow and proposes policy and technical directions for implementing a Refrigerant Management Circle (RMC) that can be applied in other countries.

JAPAN'S FLUOROCARBON MATERIAL FLOW: VISIBLE AND INVISIBLE EMISSIONS

Figure 1 illustrates the material flow of CFCs, HCFCs, and HFCs in 2008, 2015, and 2023 in

CO₂-equivalent terms. The figure integrates production/imports, equipment charging, leakage during use, releases at disposal, and recovery/reclamation/destruction.

It clearly shows that emissions at disposal remain substantial. HFC consumption has decreased in line with the reduction schedule, and Japan achieved its 2024 target with consumption at 32 million t CO₂. However, the recovery rate at disposal has stagnated at 40–44% in recent years. Despite legal obligations, a significant amount of refrigerant is released into the atmosphere. Leakage from commercial refrigeration and air conditioning equipment also remains high, with total HFC releases reaching 31 million t CO₂ in 2023.

Emissions from CFCs and HCFCs contained in insulation foams in refrigerators and buildings are difficult to quantify. Due to the long lifetime of buildings, emissions are spread over several decades. Buildings constructed from the 1970s to the 1990s contain large quantities of R11 and R12 with very high GWPs, making atmospheric release during demolition highly likely. Residual gas emissions from refrigerant cylinders are also a concern. In Japan, well over 500,000 non-refillable cylinders (NRCs) are estimated to circulate annually, and improper disposal or residual gas release poses environmental risks.

Figure 2 shows emissions of CFCs, HCFCs, and HFCs during manufacturing, use, and disposal. Manufacturing emissions are limited, while leakage during use and releases at disposal account for the majority. HCFC leakage from commercial equipment is particularly significant. Although CFC and HCFC emissions fall under the Montreal Protocol, they are not included

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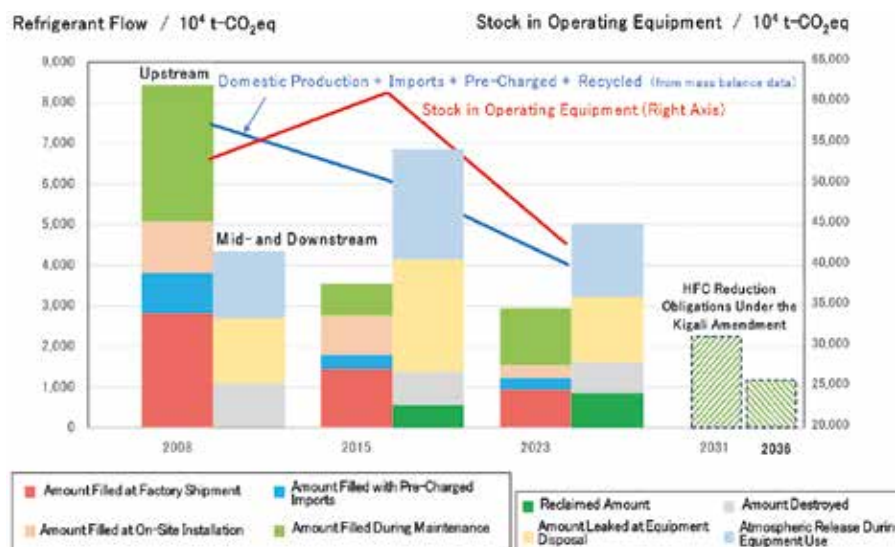


Figure 1: Material flow of CFCs, HCFCs, and HFCs in Japan in 2008, 2015, and 2023 (IPCC AR5 100-year).

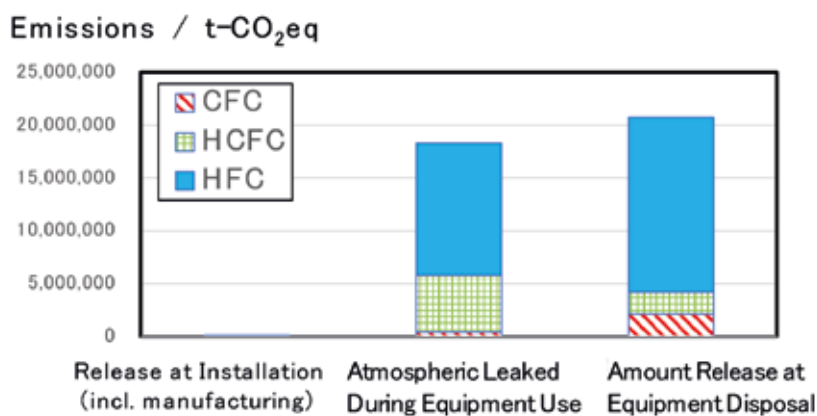


Figure 2: Emissions of CFCs, HCFCs, and HFCs in Japan by lifecycle stage (FY2023, GWP: IPCC AR5).

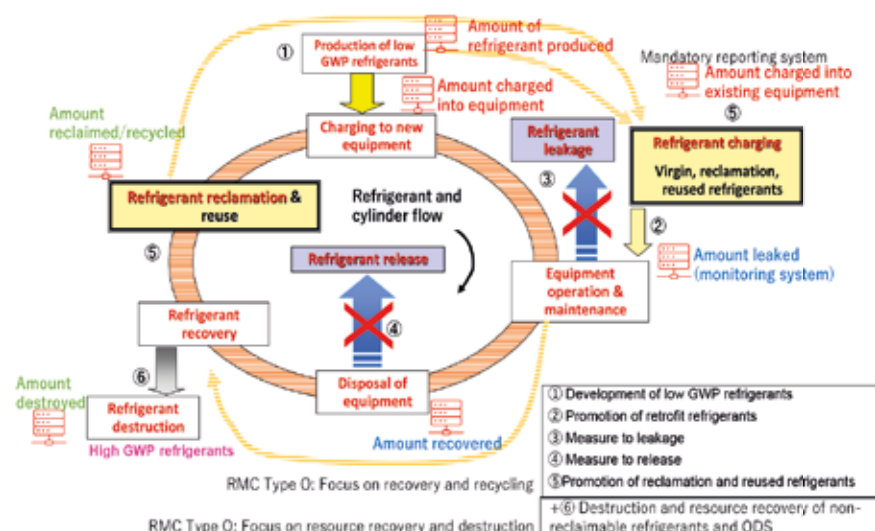


Figure 3: Concept of the Refrigerant Management Circle (RMC) and the role of management data.

insufficient data on insulation foam stocks and disposal-related emissions. Japan's insulation foam emissions represent a typical case of "invisible ODS emissions" in the global context. In many developing countries, emissions of HCFCs and even CFCs remain substantial, highlighting the need for flexible international frameworks tailored to national circumstances. In the EU, revisions to the F-Gas Regulation mandate a complete ban on NRC cylinders and require transparency in reclaimed refrigerant markets. In the United States, the American Innovation and Manufacturing (AIM) Act promotes residual gas recovery and the use of reclaimed refrigerants. In Asia, HCFC phase-out and HFC reduction are progressing simultaneously, and Vietnam has introduced a government registration system for charging and recovery quantities.

THE NEED FOR CIRCULAR REFRIGERANT MANAGEMENT (RMC)

Figure 3 presents the concept of the Refrigerant Management Circle (RMC), which integrates refrigerant supply, use, recovery, reclamation, and destruction. Data from refrigerant cylinders play a central role in enabling this circular system as cylinder level information provides traceability across the entire refrigerant lifecycle. RMC can be implemented in other countries, and similar models are already being piloted in some regions. Improving recovery rates at disposal requires standardized removal procedures, transparent recovery costs, enhanced outreach to equipment owners, and measures against informal disposal routes. Reclaimed refrigerants are important for reducing environmental impacts and promoting resource circulation, but in Japan, quality assurance systems and market transparency remain insufficient, limiting reclaimed refrigerant to about 20% of total supply. Proper cylinder management is also essential. Issues include cross-contamination of refrigerants, residual gas release, and the use or storage of corroded cylinders.

in greenhouse gas inventories under the Paris Agreement. This institutional gap weakens incentives to reduce ODS emissions. Recent studies by NOAA and UNEP

report atmospheric concentrations of R11 higher than expected, suggesting emissions from insulation foams or possible illegal production. Japan faces similar challenges, including

A system that manages the entire cylinder lifecycle is needed. Future measures should combine economic and institutional instruments, such as subsidies or buy-back programs for recovery and reclamation, incentives for using reclaimed refrigerants, and certification schemes for proper recovery operators. These measures can enhance the effectiveness of circular (Type O) refrigerant management. Type O refers to circular refrigerant management centered on recovery and reclamation. Type Q refers to a circular resource model in which refrigerants unsuitable for reclamation—including CFCs and HCFCs—are destroyed and their by-products are recovered as resources or used in material production. Establishing Type Q systems is important for both resource circulation and greenhouse gas reduction.

DIGITAL CYLINDER TRACKING AND REFRIGERANT MANAGEMENT: DEVELOPMENT AND OUTCOMES OF REFCYL

To address these challenges, the Japan Society of Refrigerating and Air Conditioning Engineers (JSRAE) developed the refrigerant cylinder management system RefCyl, which has been under pilot operation since 2023. RefCyl features QR-code identification for each cylinder, cloud-based history management, electronic recovery applications, linkage with existing systems, and an OverPlatform concept enabling cross-operator management. Digital management of both cylinders and refrigerants has strong potential for international deployment. As of June 2026, more than 80,000 cylinders have been registered and over 43,000 cylinders have been recovered. The estimated amount of recovered and reclaimed refrigerant (including residual gas) is about 17 tons, corresponding to approximately 34,000 tons of CO₂ reduction. These outcomes contribute significantly to reducing environmental impacts and preventing accidents. In addition, RefCyl enables the analysis of cylinder return time, which is a major blind spot in global refrigerant

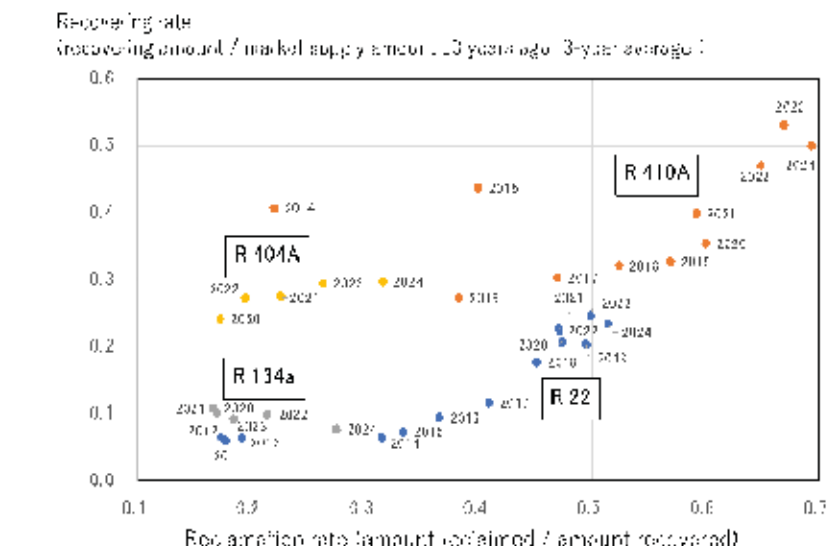


Figure 4: Relationship between recovery rates and reclamation rates based on mass balance (K Plot).

management. Preliminary data show distinct patterns among refrigerant types, such as longer return times for R22 and R404A and shorter cycles for R410A.

VISUALIZING REFRIGERANT FLOWS USING THE K-PLOT

Figure 4 shows the K-Plot, which visualizes the relationship between refrigerant recovery rates and reclamation rates⁴. A positive correlation is observed for R22, R410A, and R32 (included in the analysis but not shown in Fig.4), indicating that the use of reclaimed refrigerants contributes to higher recovery rates. In contrast, correlations for R134a, R404A, and R407C (included in the analysis but not shown in Fig.4) are weaker, suggesting that reclamation is more difficult due to processing rules or refrigerant characteristics. When combined with cylinder return time data, the K-Plot provides a unique perspective on refrigerant circularity, revealing differences in field retention and reclamation feasibility among refrigerant types.

CONCLUSION: JAPAN'S PATH TOWARD CIRCULAR REFRIGERANT MANAGEMENT

Japan's refrigerant management system is advanced by international standards, yet challenges remain: stagnant recovery rates at disposal,

uncertainties in insulation foam emissions, an underdeveloped reclamation market, and insufficient cylinder traceability. Digital systems such as RefCyl represent an important step toward achieving circular refrigerant management, particularly for Type Q, and constitute a pioneering initiative globally. This experience can contribute to the advancement of refrigerant management worldwide. Strengthening management across the entire refrigerant lifecycle will be essential to achieving both the Kigali Amendment reduction schedule and broader climate mitigation goals.



Two working meetings were held in Paris to discuss the preparation of the new edition of the International Special Issue of Industria & Formazione, promoted by Centro Studi Galileo in cooperation with UNEP - United Nations Environment Programme, the IIR - International Institute of Refrigeration, and AREA.

EU Fluorinated Gas Policy at 20: Reducing Emissions and Transforming Markets



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The European Union marks two important anniversaries in 2026: ten years since the adoption of the Kigali Amendment and twenty years since the first EU fluorinated gas (F-Gas) Regulation. Over those two decades, EU policy has evolved from improving the management of fluorinated greenhouse gases to progressively reducing their supply, restricting their use and supporting the uptake of climate-friendly alternatives.

THE FIRST F-GAS REGULATION: IMPROVING REFRIGERANT MANAGEMENT

The first F-Gas Regulation, adopted in 2006, focussed primarily on establishing good refrigerant-management practices for F-Gases across all 27 EU Member States. This included the training and certification of some 400,000 technicians, alongside mandatory requirements for leak checks, recovery and end-of-life treatment. These measures were designed to prevent emissions from equipment using F-Gases.

THE 2014 REGULATION: REDUCING HFC SUPPLY AND TRANSFORMING MARKETS

The second EU F-Gas Regulation, adopted in 2014, broke new ground. In anticipation of a global agreement under the Montreal Protocol, it introduced an ambitious quota system for hydrofluorocarbons (HFCs), triggering a transformation of the EU market. The quota system progressively reduces the quantity of HFCs that can be placed on the EU market, measured in carbon dioxide equivalent (CO₂e). This creates an incentive to reduce HFC first in sectors where doing so is most

economical and feasible. Market participants can reduce their demand for HFC quotas by:

- (i) using substances with lower global warming potential (GWP) or avoiding fluorinated gases altogether in new equipment,
- (ii) reducing refrigerant gas charges through improved equipment design,
- (iii) retrofitting existing equipment,
- (iv) minimising refrigerant losses through better servicing and regular checks, with associated improvements in energy efficiency and performance,
- (v) increasing the recycling and reclamation of used gases.

There are clear indications that all these practices have been adopted in response to the quota system. In particular, the market has shifted away from highly warming F-Gases towards gases with a much lower GWP and F-Gas free alternatives. Since 2015, the climate impact of HFCs supplied to the EU market – both in bulk and contained in equipment - has fallen to around one third of its previous level measured in CO₂e (Figure 1). Over the same period, the supply of other F-Gases not covered by the quota system increased.

ENSURING EQUAL TREATMENT OF EU AND IMPORTED EQUIPMENT

The quota system indirectly covers HFCs contained in imported equipment. It therefore treats equipment importers and EU equipment manufacturers in the same way.

The total quantity of HFCs contained in imported equipment has increased significantly over the past ten years. However, the associated climate impact, measured in CO₂e, has

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almost halved (Figure 2). This indicates a substantial shift towards gases with a lower GWP.

HOW THE REFRIGERATION SECTOR RESPONDED

The largest reductions in HFC demand have been achieved in the refrigeration sector, where many types of equipment can avoid using fluorinated gases altogether.

Transcritical CO₂ technology has become the standard for large supermarket refrigeration systems in the EU. Approximately 100,000 such systems are in operation today compared to fewer than 10,000 a decade ago. For small, self-contained refrigerated cabinets commonly used in smaller shops, hydrocarbons, and particularly propane, have become the preferred choice.

Some 20 million units using this technology are now in operation in the EU. Ammonia is also frequently used in industrial refrigeration installations, where public access is normally limited.

The quota system is widely regarded as having successfully promoted the uptake of these technologies. However, its operation also creates significant administrative burden. European and national authorities must carry out compliance checks and enforcement, while customs and market-surveillance authorities must devote considerable effort to preventing illegal activities.

COMPLEMENTING QUOTAS WITH SECTORAL PROHIBITIONS

Sectoral prohibitions have proven effective in restricting the use of high-GWP F-Gases where they are no longer needed. One example is the elimination in the EU of R404A (or R507A): highly warming refrigerant blends that offer only mediocre energy efficiency. Alongside restrictions on their use in new equipment, the 2014 Regulation prohibited the use of virgin R404A/ R507A to service certain existing equipment from 2020. This measure is commonly known as the “service ban”. Figure 3 shows the resulting decline in the EU supply of R404A.

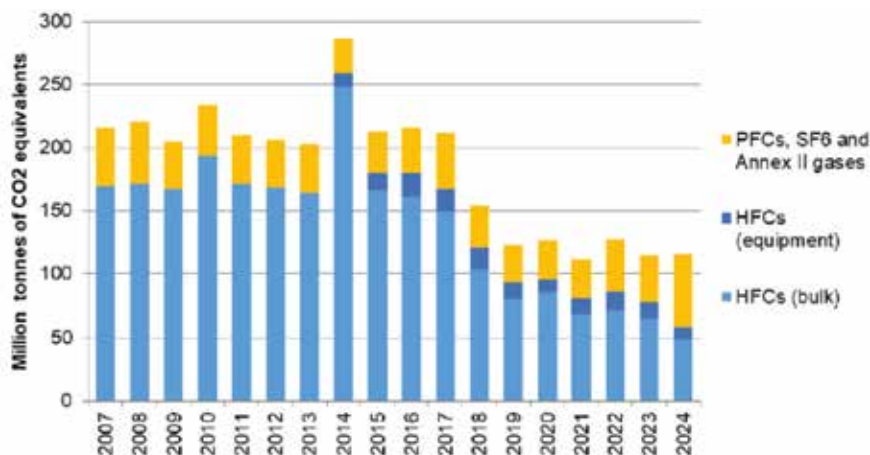


Figure 1: EU supply by type and group of fluorinated gases.



Figure 2: EU imports of fluorinated gases contained in products and equipment. The columns show metric tonnes of F-Gases and HFCs according to the left scale, while the blue lines indicate the climate effect (in CO₂ equivalents) according to the right.

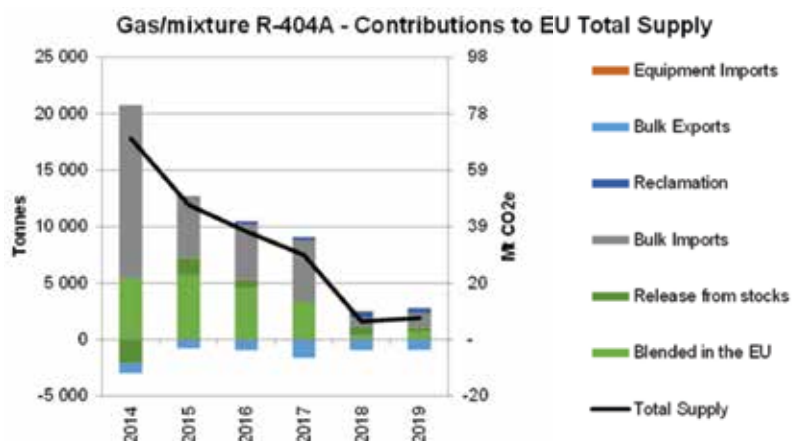


Figure 3: EU supply of R404A.

THE 2024 REGULATION: TOWARDS AN HYDROFLUOROCARBONS PHASE-OUT

Rapid technological progress across many sectors paved the way for the third EU F-Gas Regulation adopted in

2024. The Regulation provides for the complete phase-out of HFCs by 2050 and introduces numerous additional sectoral prohibitions, particularly in the air conditioning sector. Some of these prohibitions require certain types of equipment, including smaller heat pumps and chillers, to avoid

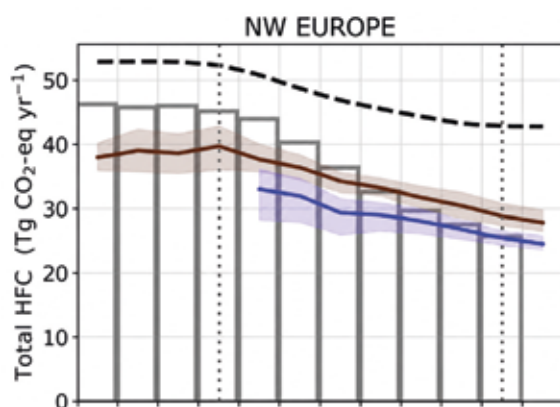


Figure 4: Annual emissions of total HFCs for north-western Europe from 2013 to 2025. While columns represent data reported to the UNFCCC, the black and blue solid lines are derived from inverse modelling based on atmospheric observations.

F-Gases altogether. In addition to reducing greenhouse gas emissions, moving away from these gases can help address concerns related to per- and polyfluoroalkyl substances (PFAS), commonly known as “forever chemicals”. A broad EU assessment of potential further restrictions on PFAS is ongoing. It may result in additional restrictions where suitable non-PFAS alternatives are available. The 2024 Regulation also introduced clearer rules to facilitate enforcement. In addition, technicians must now be trained and certified to work with all refrigerants, fluorinated or not, in both stationary and mobile applications. This broader training requirement is crucial for the transition. Many climate-friendly refrigerants have properties, including flammability, that require specialised skills and knowledge to ensure that equipment is installed, serviced and handled safely.

EXTENDING ACTION TO MOBILE EQUIPMENT

EU market placement bans currently only cover stationary cooling and heat pump equipment as well as air conditioning systems in passenger cars. In 2027, the European Commission will report on the possibilities for replacing F-Gases in all mobile equipment that uses refrigeration and/or air-conditioning. This report is likely to provide a key input into the overall review of the F-Gas Regulation, which is legally required by 2030.

ATMOSPHERIC MEASUREMENTS CONFIRM FALLING EMISSIONS

Recent atmospheric monitoring provides further evidence of the impact of EU F-Gas policies. Researchers have observed a steady decline in total HFC emissions over north-western Europe (Figure 4), while global emissions of most HFCs continue to increase.

SHARING LESSONS FROM EU EXPERIENCE

The EU experience demonstrates the value of combining an ambitious quota system with targeted prohibitions on placing certain F-Gas equipment on the market and appropriate flexibilities. This combination of policy tools is particularly important in markets where replacing high-GWP

F-Gases remains more technically or economically challenging. It has enabled continuous, gradual progress across all sectors of the EU economy. EU F-Gas policies have enabled the Union to meet its obligations under the Kigali Amendment to the Montreal Protocol and now go significantly beyond those requirements. Many countries operating under Article 5 of the Protocol are currently developing their own policies to implement the Amendment. The transformation of the EU refrigeration and air-conditioning market has resulted in a wide range of new equipment using climate-friendly refrigerants. This should make it easier for other countries to design policies capable of delivering rapid results. For example, targeted bans may be particularly effective where alternatives to F-Gases have already become technically mature and widely used. The EU is working bilaterally with other countries to exchange our experiences of different approaches to implementing the Kigali Amendment.

Overall, the EU experience shows that an effective policy framework must:

- Avoid the use of F-Gases where suitable alternatives are available;
- Minimise emissions where F-Gases continue to be used;
- Ensure that installers and technicians have the necessary skills;
- And establish effective rules for implementation and enforcement.



The AREA–UNEP side event on the training manual on good servicing practices and energy efficiency, held in Bangkok during the OEWG, the Open-ended Working Group of the Parties to the Montreal Protocol, attracted strong international participation.

10 Years of the Kigali Amendment: Turning Ambition into Action through Skills, Certification and Implementation



Stepan Stojanov

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In 2016, the adoption of the Kigali Amendment to the Montreal Protocol marked a historic milestone in global climate policy. By committing countries worldwide to progressively phase down hydrofluorocarbons (HFCs), the international community set a clear course towards more sustainable cooling solutions.

Ten years later, the Kigali Amendment has proven to be a powerful catalyst for change. Across Europe and beyond, the refrigeration, air conditioning and heat pump (RACHP) sector has embraced the transition towards lower-GWP refrigerants, while manufacturers have brought innovative technologies to the market and policymakers have strengthened regulatory frameworks. The European Union has been at the forefront of this transformation through its F-Gas legislation, which translates the objectives of Kigali into concrete measures and ambitious phase-down schedules.

However, as we reflect on a decade of progress, it is becoming increasingly clear that legislation alone does not deliver results. The success of the Kigali Amendment will ultimately depend on how effectively it is implemented on the ground. For AREA, representing refrigeration, air conditioning and heat pump contractors across Europe, the next phase of the transition is about ensuring that the workforce responsible for installing, maintaining, servicing and replacing equipment has the skills, knowledge and certification required to make the transition a success.

CONTRACTORS AT THE HEART OF THE TRANSITION

The RACHP sector plays a unique role in delivering climate objectives. While policymakers

establish regulatory frameworks and manufacturers develop innovative technologies, contractors transform these ambitions into reality. They are responsible for selecting, installing and maintaining equipment that ensures safe operation, optimal energy efficiency and minimal environmental impact throughout the system's lifetime.

This role is becoming increasingly complex. The transition away from conventional HFCs has accelerated the adoption of refrigerants with significantly lower global warming potential, including natural refrigerants such as carbon dioxide (CO₂), ammonia and hydrocarbons, as well as new synthetic alternatives. Many of these solutions bring important environmental benefits, but they also require different installation practices, specialised technical knowledge and enhanced safety procedures.

As the market evolves, contractors are expected to master a growing range of technologies while ensuring compliance with increasingly demanding regulatory requirements. The quality of their work directly influences safety, energy performance, refrigerant containment and overall environmental outcomes. In this context, investing in skills and competence is fundamental to achieving the objectives of the Kigali Amendment.

SKILLS AS THE MISSING LINK

One of the greatest challenges facing the sector today is the widening gap between the deployment of new technologies and the availability of appropriately trained technicians. Europe already has a substantial workforce of F-Gas-certified technicians. However, certification obtained under previous regulatory

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frameworks does not automatically guarantee competence in handling the latest generation of refrigerants and equipment. Many of the alternatives entering the market involve flammable, mildly flammable or high-pressure refrigerants that require additional expertise and specific safety measures.

Without adequate training, the transition could face significant obstacles. Improper installation or servicing may compromise safety, reduce energy efficiency, shorten equipment lifetimes and undermine environmental performance. In parallel, a shortage of qualified technicians could slow the deployment of sustainable cooling technologies and heat pumps at a time when Europe is striving to accelerate decarbonisation.

The challenge is therefore not simply one of numbers. It is about ensuring that technicians possess the right skills to work safely and competently with modern refrigerants and systems. This requires continuous professional development, updated curricula and accessible training opportunities throughout Europe.

A NEW FRAMEWORK FOR TRAINING AND CERTIFICATION

Recognising these challenges, the revised EU F-Gas Regulation introduced a stronger focus on skills and competence. A key element of this framework is Commission Implementing Regulation (EU) 2024/2215, which updates the minimum requirements for the certification of natural persons and companies undertaking activities involving fluorinated greenhouse gases and alternative refrigerants.

The implementing act is far more than a technical update. It provides the foundations for a workforce capable of supporting the transition towards sustainable cooling.

For AREA, the importance of this legislation cannot be overstated. The implementing act establishes a common baseline across Europe and helps ensure that technicians develop the competencies needed to handle low-GWP refrigerants safely and effectively. At a time when

the sector is undergoing profound technological change, harmonised training requirements are essential to maintain high standards and facilitate mobility across Member States.

However, the existence of legislation alone is not enough. Its value will depend entirely on effective implementation.

THE CRUCIAL ROLE OF MEMBER STATES

The responsibility for establishing and operating certification schemes ultimately rests with Member States. National authorities must transpose European requirements into practical systems that allow technicians and companies to obtain the necessary qualifications and maintain their competence over time.

This makes implementation the critical success factor for the coming decade.

Some countries have already demonstrated what effective implementation can achieve. The Netherlands, for example, has developed a comprehensive certification framework covering both technicians and companies. In anticipation of the new framework, the Dutch refrigeration sector, government authorities, certification bodies and training providers have worked together to develop and implement new certification schemes. These schemes

encompass fluorinated refrigerants as well as alternative refrigerants such as hydrocarbons, CO₂ and ammonia. Significant investments have been made in developing new examinations, training installations and other materials, and certification procedures. To support workforce readiness, the Dutch association NVKL has also developed an online learning platform that enables technicians to prepare for the theoretical certification examinations through dedicated learning modules covering refrigerants, legislation and safety requirements. As a result of these efforts, the new certification schemes are now in effect in the Netherlands, thereby providing the framework for safe and competent handling of both F-Gas systems and those containing alternative refrigerants. This illustrates how early preparation and close cooperation between industry and government can facilitate the practical implementation of the revised F-Gas framework. Such approaches help create a culture of competence, accountability and continuous improvement while providing confidence to customers and authorities alike.

At the same time, implementation remains uneven across Europe. Differences in training capacity, certification structures and enforcement practices can create inconsistencies that risk undermining



The AREA family, representing 25 associations of refrigeration and air-conditioning technicians, gathered in Madrid last May. The city also hosted the presentation of awards recognising outstanding women in cooling and the sector's best young professional.

the objectives of the legislation. A fragmented approach may also create barriers for companies operating across borders and complicate the development of a truly skilled European workforce. AREA therefore encourages all Member States to ensure timely and effective implementation of the updated certification requirements, while working closely with training providers, contractors, manufacturers and industry associations.

ADDRESSING THE SKILLS SHORTAGE

The success of the cooling transition also depends on attracting new talent into the profession.

The RACHP sector is experiencing increasing demand driven by the growing need for sustainable cooling, electrification and heat pump deployment. At the same time, many countries face ageing workforces and difficulties recruiting young people into technical professions.

Addressing this challenge requires a long-term strategy that combines vocational education, apprenticeship programmes, continuous training and awareness-raising initiatives. The sector must promote itself as an attractive and future-oriented career path offering stable employment, technological innovation and a direct contribution to climate objectives.

Investment in training infrastructure is equally important. Training centres need access to modern equipment and qualified instructors capable of teaching the latest technologies. Public authorities should recognise skills development as a strategic component of climate policy and ensure that adequate funding mechanisms are available. The green transition cannot succeed without the people who make it happen. It will be delivered by hundreds of thousands of skilled technicians working every day to install, service and maintain the systems on which modern society depends. Ensuring their competence through robust certification systems, high-quality training and effective national implementation is therefore essential. The revised F-Gas framework and Implementing

Regulation (EU) 2024/2215 provide the necessary foundation, but their success depends on the commitment of Member States, industry stakeholders and training organisations to make them work in practice.

SUPPORTING GLOBAL CAPACITY BUILDING

While the European Union has established one of the world's most advanced regulatory frameworks for fluorinated gases, the transition to sustainable cooling is a global challenge that requires international cooperation. AREA actively promotes the transfer of the European approach to technician training, certification and good servicing practices, supporting developing countries—particularly those under Article 5 of the Montreal Protocol—in strengthening their national capacity and aligning with internationally recognised standards. One example of this commitment is AREA's long-standing collaboration with the United Nations Environment Programme (UNEP) OzonAction Programme, through which it contributed to the development of the Training Manual on Refrigerants, Servicing and Good Practices, which provides practical guidance on refrigerant management, leak prevention, recovery, safety and energy-efficient servicing. The manual serves as a practical resource for capacity-building activities and supports

countries in developing competent workforces capable of implementing the Kigali Amendment effectively. In parallel, AREA actively participates in international discussions under the Montreal Protocol, including the Open-ended Working Group (OEWG) and the Meeting of the Parties (MOP), where it shares the European experience as an example of effective implementation of certification schemes, technician training and regulatory enforcement in the RACHP sector. By promoting the European model and exchanging practical experiences with policymakers, industry representatives and training organisations worldwide, AREA contributes to the development of robust national qualification systems and helps countries accelerate the transition towards safe, energy-efficient and climate-friendly cooling technologies.

CONCLUSION

Ten years after Kigali, the direction of travel is clear. The challenge now is to ensure that Europe has the skilled workforce needed to complete the journey. By strengthening certification, accelerating training on alternative refrigerants and promoting consistent implementation across Member States, we can turn policy ambition into real-world progress and build a safer, more efficient and more sustainable cooling sector for the future.



UNEP-AREA Training Manual
Refrigerants Servicing and Good Practices

The UNEP-AREA Refrigerants Servicing and Best Practices Manual is a comprehensive training resource designed to support refrigeration and air-conditioning (RAC) technicians in the safe, efficient, and environmentally responsible use of refrigerants.

The Legacy of Kigali: Energy Efficiency, Environmental Protection, Safety



Bill McQuade

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American Society of Heating,
Refrigerating and Air-Conditioning
Engineers (ASHRAE), 2025-2026*

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ASHRAE has a long history of improving the quality of life.

The Society has made important contributions to improving energy efficiency and decarbonizing buildings—and, through the development of industry standards, research into refrigerant properties and applications, and education and training, ASHRAE has helped lead global efforts to eliminate ozone-depleting refrigerants and transition to environmentally preferable alternatives.

As the refrigeration and air-conditioning industry recognizes the 10-year anniversary of the adoption of the Kigali Amendment to the Montreal Protocol, ASHRAE remains fully committed to supporting its vision and implementation.

The Kigali Amendment established a global schedule for reducing the production and consumption of hydrofluorocarbons (HFCs), powerful greenhouse gases widely used as refrigerants.

Full implementation is expected to avoid up to approximately 0.3–0.5°C of global warming by 2100. But Kigali's impact extends well beyond the refrigerant itself. It affects the equipment we manufacture, the buildings we design, the systems we

install and operate, the technicians who service them, and the policies and standards that govern their use. That is why Kigali implementation requires more than replacing one refrigerant with another.

The transition must also be safe and energy efficient.

WHY ENERGY EFFICIENCY MATTERS

Cooling demand continues to grow, particularly in developing economies. HFCs do not deplete the ozone layer, but many have global warming potentials hundreds or thousands of times greater than carbon dioxide.

Lower-GWP alternatives have therefore been developed and introduced, some with different safety characteristics, including increased flammability.

At the same time, refrigerant choice alone does not determine the climate impact of a cooling system. If equipment is inefficient, increased electricity consumption—and the associated CO₂ emissions from electricity generation—can offset part of the climate benefit achieved by switching refrigerants.

The Kigali transition therefore presents an opportunity to address both direct emissions from refrigerants and indirect emissions associated with energy consumption. High-efficiency cooling equipment, better building design, proper system sizing and optimization, energy-efficient servicing practices and responsible refrigerant management all contribute to the solution.

ASHRAE's role is particularly important at the point where international environmental commitments must be translated into engineering requirements and everyday practice.

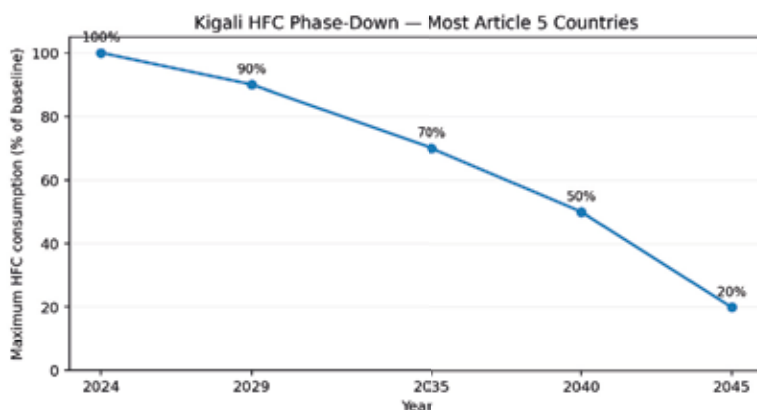


Figure 1: Kigali HFC phase-down for most Article 5 countries. Consumption froze at the baseline level in 2024 and is progressively reduced to 20% of baseline by 2045.

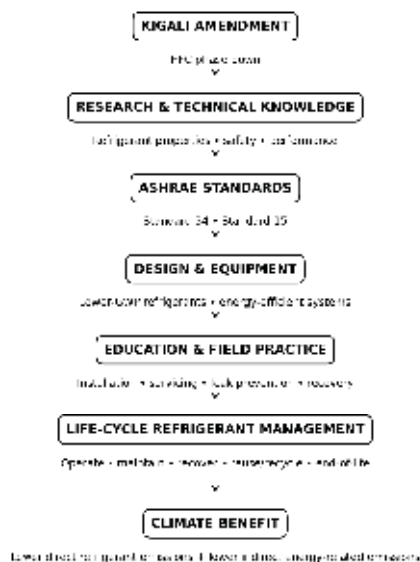


Figure 2: From Kigali commitment to climate benefit. ASHRAE helps bridge international environmental commitments and implementation through research, standards, education and field practice.

TURNING KIGALI COMMITMENTS INTO PRACTICE

The Kigali Amendment establishes the direction and timetable for reducing HFC consumption. Implementation ultimately takes place in equipment, buildings and the refrigeration and air-conditioning workforce. This is where ASHRAE makes a distinctive contribution. ASHRAE helps provide the technical infrastructure needed to make the transition possible. The Society translates scientific and engineering knowledge into standards, guidance, research, education and practical tools that can be used by designers, manufacturers, engineers, building owners, operators and service technicians. That support can be viewed as four interconnected activities: research and technical knowledge, standards, education and workforce development, and life-cycle refrigerant management.

RESEARCH AND TECHNICAL KNOWLEDGE

A successful refrigerant transition begins with understanding the alternatives and understanding how they can be used safely and effectively

in real-world applications. ASHRAE-sponsored research and the ASHRAE Handbook contribute technical information needed to understand refrigerant properties, system performance, safety and application requirements. As the industry prepared for the transition to lower-GWP refrigerants, ASHRAE also played an important role in assessing the risks associated with these alternatives. Through the ASHRAE Low GWP Refrigerants Modeling and Simulation Technical Committee (Low GWP MTG), the Society supported significant risk-assessment research to better understand how lower-GWP refrigerants could be used safely and effectively. This work was part of a broader industry effort. ASHRAE collaborated with the U.S. Department of Energy and its national laboratories, AHRI and companies across the industry to conduct research, evaluate technical challenges and develop the information needed to support the transition. The work brought together expertise from across the refrigeration and air-conditioning community and helped address the practical questions involved in moving from one generation of refrigerants to the next. That collaborative effort helped bridge the gap between identifying lower-GWP alternatives and putting them into practical use. It provided important technical information to support standards, codes, equipment design and safe application, helping to make the transition both practical and possible.

STANDARDS FOR A SAFE TRANSITION

Safety is fundamental to Kigali implementation because some lower-GWP alternatives have different flammability or toxicity characteristics than the refrigerants they replace. ANSI/ASHRAE Standard 34, Designation and Safety Classification of Refrigerants, establishes a uniform system for assigning refrigerant numbers, safety classifications and refrigerant concentration limits. ANSI/ASHRAE Standard 15, Safety Standard for Refrigeration Systems, establishes requirements for the safe design, construction, installation and

operation of refrigeration systems. Together, Standards 15 and 34 help turn the introduction of new refrigerants into engineering requirements that protect people and property. They also reflect the research, risk assessment and industry experience that have informed the transition to lower-GWP refrigerants. These standards provide a technical basis that can be incorporated into national and regional codes and regulations as countries implement their refrigerant transitions.

EDUCATION AND WORKFORCE DEVELOPMENT

Standards alone are not enough. The engineers who design systems and the technicians who install, operate, maintain and repair them must understand how refrigerants differ and how those differences affect their work. This becomes particularly important as technicians encounter mildly flammable A2L refrigerants and, in some applications, highly flammable A3 refrigerants. Safe practices may require different tools, leak-detection procedures, ventilation, refrigerant recovery practices and precautions against potential ignition sources. ASHRAE supports the transition through publications, technical guidance, eLearning and other educational resources. Through its partnership with the United Nations Environment Programme's OzonAction programme, these resources can also support capacity building in developing countries, where much of the future growth in refrigeration and air conditioning will occur.

A GLOBAL PARTNERSHIP FOR IMPLEMENTATION

Developing countries face particular challenges in making this transition. Equipment must change, standards and regulations must evolve, and large numbers of technicians and engineers need access to appropriate information and training. ASHRAE and the United Nations Environment Programme have worked together since 2007 to help meet that need. The partnership

Implementation Need	ASHRAE Contribution
Understand alternative refrigerants	Research, ASHRAE Handbook and technical information
Identify and classify refrigerants	ASHRAE Standard 34
Apply refrigerants safely	ASHRAE Standard 15
Improve system efficiency	Standards, guidance, research and training
Develop workforce capability	eLearning, publications, university and technician resources
Reduce leaks and refrigerant emissions	Life-Cycle Refrigerant Management guidance
Improve operation and servicing	RAC Plant Sustainability checklists and guidance sheets
Demonstrate successful transitions	Lower-GWP case studies
Support developing countries	ASHRAE–UNEP OzonAction partnership and National Ozone Unit engagement

Figure 3: ASHRAE's Kigali implementation toolbox. Kigali implementation requires more than selecting a replacement refrigerant; ASHRAE resources support the full technical chain.

combines UNEP OzonAction's role in assisting developing countries with their Montreal Protocol obligations with ASHRAE's technical expertise, standards and international network of HVAC&R professionals. In 2026, ASHRAE and UNEP adopted a new two-year work plan focused on Life Cycle Refrigerant Management (LCRM). The work plan looks beyond refrigerant selection to consider the refrigerant throughout its useful life—from production and installation through operation, servicing, recovery, reuse and eventual disposal. The 2026–2027 program includes development and expansion of practical tools and educational products, including a multilingual technician field companion, fact sheets, eLearning, university materials, RAC Plant Sustainability resources, refrigerant information and case studies demonstrating successful lower-GWP applications.

MANAGING REFRIGERANTS FROM CRADLE TO GRAVE

One of the lessons of earlier refrigerant transitions is that refrigerant management cannot end when equipment is installed. A refrigerant may remain in a system for years or decades. During that period, emissions can occur through leaks, servicing, improper charging and equipment failure. Additional emissions can occur when equipment reaches the end of its useful life if the remaining refrigerant is not properly recovered. Preventing leaks provides a double benefit. It

prevents direct emissions of refrigerant while also helping equipment maintain its intended efficiency. Recovery and responsible end-of-life management are equally important. This is why ASHRAE's approach increasingly brings refrigerant management, energy efficiency and safety together rather than treating them as separate objectives.

PUTTING LIFE-CYCLE MANAGEMENT INTO PRACTICE

A good example is the ASHRAE–UNEP Assessing RAC Plant Sustainability technical guidance. The resource provides practical checklists that operators can use to assess whether refrigeration and air-conditioning plants are being operated in ways that are safe, energy efficient and environmentally sustainable.

- Safe storage and proper handling of refrigerants
 - Periodic leak checking and proper documentation
 - Preventive maintenance of equipment
 - Preventive maintenance of automatic controls
 - Energy-efficient operation
 - Proper commissioning and recommissioning practices
 - Proper disposal of equipment and refrigerant
 - Competencies of operating and service personnel, including requirements for tools and servicing
- This is an example of how the Kigali transition moves from policy to

practice: an international commitment becomes an engineering standard, a training program, a maintenance procedure or a technician's checklist. The Assessing RAC Plant Sustainability technical guide is available for free download at ashrae.org/UNEP-RACchecklists.

KIGALI'S BROADER LEGACY

Ten years after the Kigali Amendment was adopted, its legacy is becoming clearer. Kigali established a pathway for reducing the climate impact of HFC refrigerants. But its implementation is also accelerating changes throughout the refrigeration and air-conditioning industry—in refrigerants, equipment, system design, standards, training, servicing and refrigerant management. Those changes come at a time when the need for cooling is increasing around the world. The challenge is therefore not simply to provide more cooling, but to provide it without unnecessarily increasing energy demand, greenhouse gas emissions or safety risks. ASHRAE's goal is to help ensure that this transition occurs with minimum disruption to end users and as safely and efficiently as possible. Refrigerant choice cannot be separated from equipment efficiency; equipment efficiency cannot be separated from building design and operation; and environmental performance cannot be separated from the health, comfort and safety of occupants. The challenges are substantial, but they are not insurmountable. Our industry has already developed much of the equipment, standards, knowledge, tools and workforce needed to meet them. The work now is to build on that foundation and apply it consistently around the world. The Kigali Amendment gave the world a direction. The task now is implementation. For ASHRAE, that means continuing to connect environmental protection, energy efficiency and safety and helping translate global environmental commitments into practical engineering solutions that work in buildings and communities around the world.

From “Kigali + 10”, to “Kigali + 20” The 2026-2036 Decade



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ABSTRACT

The 2016 Kigali Amendment is a legally binding international agreement signed by 173 countries to phase down HFCs, thereby reducing greenhouse gas emissions. The implementation of “Kigali” is projected to reduce the temperature impact of HFC emissions to < 0.05 °C by 2100, still contributing to the Paris Agreement targets. Since 80% of global HFC consumption is tied to electricity-powered RACHP equipment, energy efficiency improvements in HFC conversions is important to significantly reduce emissions from fossil-fuel-based electricity generation. Recent efforts have primarily focused on achieving net-zero emissions by 2050 through cuts in fossil fuel use and large-scale replacement by renewable energy. As global energy consumption patterns evolve, new factors continue to influence the transition from fossil fuels to renewable energy. The USA-Israel vs Iran conflict convinced many countries to “renew” expansion of renewable energy capacity for energy security reasons. This likely expansion during 2026–2036 will coincide with the second decade of Kigali implementation of HFC phase-down projects, while continued improvements in energy efficiency will remain important. However, reducing RACHP demand is also critical to lowering fossil fuel dependence and matching energy use with growing renewable and battery storage capacity. The RACHP sector also needs to address how to avoid PFAS and TFA-producing refrigerants when transitioning to non-fluorinated alternatives and/or by adopting novel, high-efficient non-vapor compression technologies, thereby reducing demand. Supply-side measures

should be complemented by demand-side policies.

Reducing demand requires addressing both active and passive measures, with passive strategies expected to play an increasingly important role. Investment costs per kW installed for both active and passive measures, relative to the cost per kW of renewable energy capacity, will be a key determining factor.

THE KIGALI AMENDMENT AND RELATED ACTIONS

The 38th Meeting of the Parties (MOP-38) to the Montreal Protocol, likely to be held in Kigali, Rwanda, in November 2026, will mark the 10th anniversary of the Kigali Amendment, a legally binding amendment to the Montreal Protocol.

As of April 2026, 173 countries ratified the Amendment, which implies that 25 countries have not yet ratified (UNEP, 2026). The Kigali Amendment mandates a phased reduction in HFC production and consumption, thereby reducing HFC emissions.

Implementation of the Kigali Amendment is projected to limit the temperature impact of HFC emissions from up to 4 °C --in case of unrestricted growth-- down to <0.05 °C by 2100 (Fig. 1), thereby still contributing to the achievement of the Paris Agreement temperature goals (see Fig. 1). Paragraph 22 of the Kigali Decision XXVIII/2 emphasizes maintaining or improving energy efficiency during the transition from HFCs to alternative refrigerants. Following the Amendment’s adoption, energy efficiency became a key focus, as improvements in equipment efficiency could reduce greenhouse gas emissions even more than the HFC phase-down alone. Since about 80% of global HFC consumption

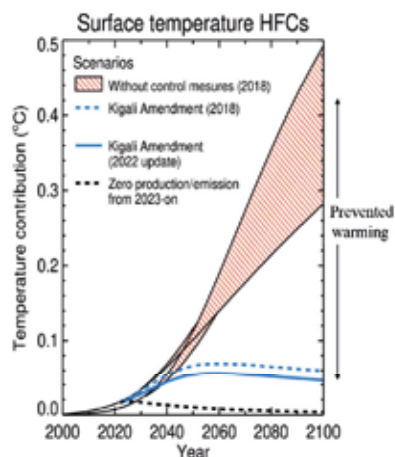


Figure 1: Temperature contribution with, and without the Kigali Amendment for HFCs (2018). The Kigali Amendment limits warming in 2100 to $<0.05^{\circ}\text{C}$; zero production from 2023 on brings the warming in 2100 back to virtually zero.

is linked to electricity-powered RACHP equipment, improving energy efficiency during refrigerant transitions can significantly reduce emissions from electricity generation. The magnitude of these reductions depends on the carbon intensity of the electricity supply, as well as equipment operation, refrigerant leakage, and energy consumption. It is therefore virtually impossible to relate the HFC temperature contribution -shown in Fig. 1- directly to CO_2 emissions (and the related global temperature increase) from electricity generation because future electricity generation mixes and equipment energy efficiency cannot be projected accurately over the period 2020–2100.

In response to various Montreal Protocol decisions, TEAP and its Energy Efficiency Task Forces published numerous reports during 2017-2022 on this issue. The reports did not refer to the overall GHG reductions as recommended by the IPCC in the 1.5°C report, although such an assessment might have been expected. These developments led to efforts to fund HFC reduction and energy efficiency projects through the Montreal Protocol Multilateral Fund.

With some delays (mainly due to COVID-19), guidelines for addressing HFC reductions and energy efficiency

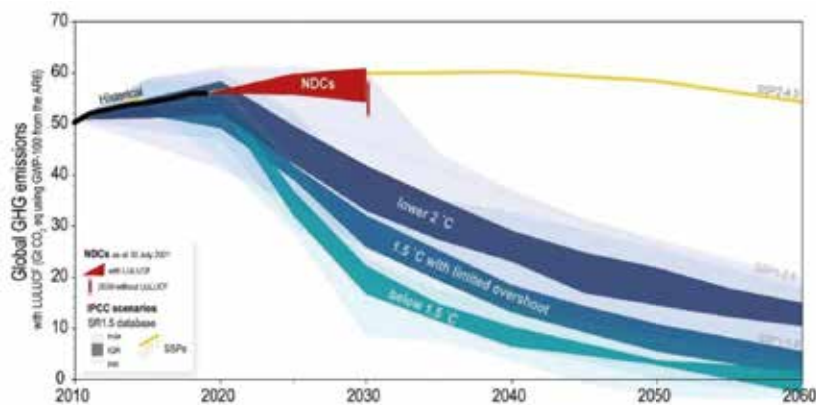


Figure 2A: Emission reductions required for 2°C and 1.5°C targets (2022–2050) compared with current, insufficient NDC projections.

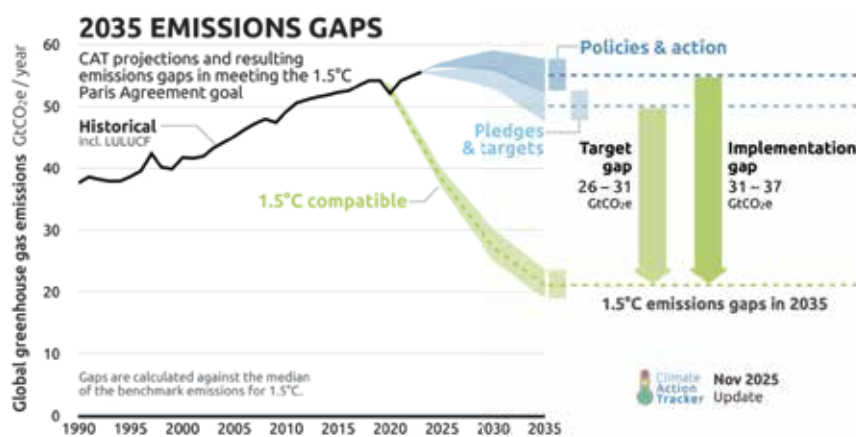


Figure 2B: 2025 clarification of Figure 2A, where it concerns emissions gaps. Emissions continue to rise under current policies, leaving a 31–37 Gt CO_2 -eq gap to the 1.5°C pathway by 2035 and resulting in projected warming of 2.5 – 3.2°C by 2100.

in Kigali Implementation Plans (KIPs) have become standard practice, so the whole approach became more or less Business-As-Usual in the years 2025-26.

This is a significant outcome, ten years after the adoption of the Kigali Amendment, now ratified by all major producing and consuming countries.

WHAT ABOUT NET-ZERO?

Following the 2015 Paris Agreement – which mentions 2°C (and preferably 1.5°C) as targets for the global temperature increase by 2100 – the IPCC 1.5°C Special Report outlines pathways for the mitigation of climate change to keep long-term warming below 1.5°C as the long-term temperature average. The report also states that: (1) reductions in net emissions can be achieved through consistent portfolios of mitigation measures (i.e., NDCs, Nationally

Determined Contributions), and (2) future radiative forcing resulting from cumulative greenhouse gas emissions determine the probability of limiting warming to 1.5°C . To achieve net zero, global greenhouse gas emissions (Fig. 2A/B) would need to decline by about 45% from 2010 levels by 2030, reaching net zero around 2050, consistent with the net-zero pathway.

Under the Paris Agreement, countries committed to reducing emissions through voluntary Nationally Determined Contributions (NDCs). Approaches to emission reductions differ between Annex I (developed) and non-Annex I (developing) countries, for which further information can be found in Kuijpers et al. (2022-24). Many governments initially adopted long-term NDC visions, but these have had limited short-term impact, as near-term measures rely on

policies and projections that are increasingly affected by geopolitical developments. Figure 2 illustrates the gap between current NDC trajectories and the net-zero pathway. During 2023-2026, many stated that not enough was done to transform society to “net zero”: “Current global climate action is starkly insufficient”, and “We are not on track” (summary by Stiell (2026)). Current projections indicate that emissions during 2026–2050 are likely to result in 2.7–3.2 °C of warming by 2100. The net-zero target and limiting warming to 1.5 °C by 2050 are now widely viewed as unlikely to achieve. This shift was reflected in studies published during 2024–2026; these reports forecast sustained periods of global temperatures above 1.5 °C and increasing risks of climate tipping points, regional climate shifts, more frequent heat waves, and accelerated polar ice loss.

Achieving net zero depends largely on the transition to renewable energy. This was also the major issue for the forecast of emissions reductions by. However, since 2024-2025 many global supply and economic issues have changed, resulting in:

(1) The rise of climate-sceptic policies in some countries has slowed or reversed fossil-fuel phase-down efforts and, in some cases, encouraged renewed fossil-fuel use.

(2) In 2025, the United States promoted expanded oil drilling and hydraulic fracturing, with similar initiatives emerging elsewhere (edie, 2026). However, fossil-fuel production growth has been mainly driven by natural gas.

(3) Where COP30 was not able to address fossil fuel phase-downs, a separate conference in Santa Marta, Colombia addressed it in April 2026, but it is not yet clear whether and how this will impact future conferences such as the next COP31 in 2026.

(4) The evolving conflict involving the United States and Iran has renewed emphasis on fossil fuels, while also strengthening energy security arguments for expanding renewable energy, as well as greater reliance on natural gas

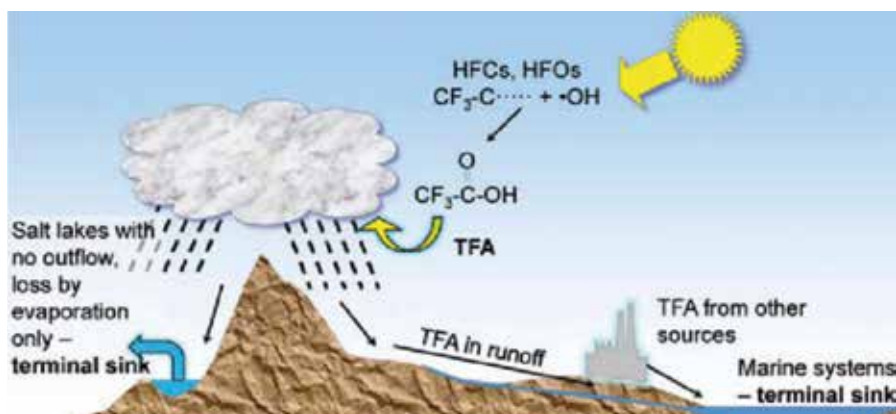


Figure 3: Trifluoroacetic acid (TFA) formed from HFCs and HFOs transfers rapidly from the atmosphere to water, accumulating in soils, salt lakes, and oceans. TFA from HFCs and HFOs is quantifiable, unlike natural and other anthropogenic sources.

and nuclear power for baseload electricity.

(5) The IEA projects that global fossil fuel consumption will peak around 2030 after which renewables are expected to gain further market share, supported by advances in energy storage. The rapid development of sodium-ion batteries could significantly reshape electricity storage.

Recently, the Montreal Action Plan, launched by the IEA, emphasized the dual priorities of long-term energy efficiency improvements and short-term energy security, particularly regarding oil and gas. As IEA Executive Director Fatih Birol stated, “The world will need oil and gas for years to come, based on trust and predictability”.

As mentioned, current projections indicate that the trajectory to 2100 will lead to global temperature increases in the range of 2.7–3.2 °C.

In this context, while the Kigali Amendment can be considered a climate action measure avoiding a significant temperature rise by 2100 from HFCs, could any future Kigali adjustment have a meaningful influence on the expected global temperature rise by 2100?

THE NEXT DECADE: THE COMBINED IMPACT OF TWO KEY DRIVERS

The temperature impact of the Kigali Amendment by 2100 is small compared with the projected global temperature increase of >2.7 °C

(2.7–3.2 °C), even when accounting for potential emissions from fossil fuel-based electricity used by HFC equipment. Nevertheless, the Kigali contribution is something that really contributes, also from a global policy perception.

Work under the Amendment is progressing, and Parties are expected to meet the phase-down schedules.

During 2026–2036, HFC phase-down and RACHP energy efficiency improvements will remain critical, through low-GWP alternatives, more efficient equipment, and potentially advanced non-vapor-compression technologies, although the time required for these technologies to mature and their investment costs remain uncertain.

However, reducing RACHP demand is also very much related to lowering fossil fuel dependence and matching energy use with growing renewable and battery storage capacity (see under the ACTIONS AFFECTING DEMAND section below). Particularly, the conversion to sodium-ion batteries is very promising.

RACHP BEYOND KIGALI: THE NEXT DECADE OF ACTION

The RACHP sector may need to avoid PFAS- and TFA-forming refrigerants (see for an artist’ impression Fig. 3) by adopting non-fluorinated alternatives or advanced non-vapor-compression technologies; HFO conversions may

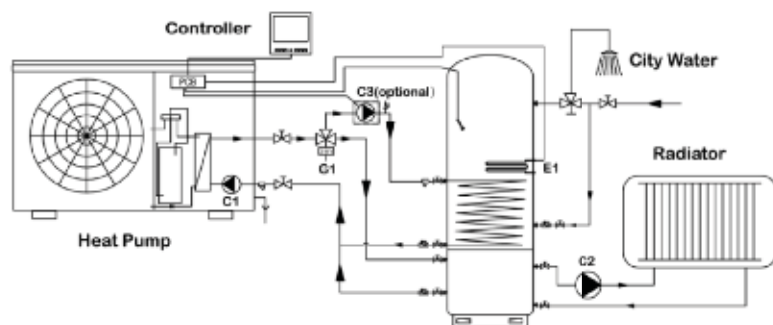


Figure 4: Air-to-water R-290 heat pump.

also face regulatory limits.

This raises major questions regarding the future regulatory treatment of the ongoing large-scale HFO-1234yf use in mobile air conditioning.

It implies two questions: (1) will all countries be able to comply with Kigali using low-GWP alternatives, and would it necessitate the use of HFOs, and (2) will HAT countries be ready to rapidly phase-down HFCs, and would they be prepared to use non-fluorinated refrigerants. More robust evidence will be needed to guide the selection of low- or near-zero-GWP alternatives.

The transition may increasingly favor non-fluorinated refrigerants and refrigerant-free technologies with very high energy efficiency. Ideally, low-GWP options in highly efficient, renewable-powered equipment, such as propane heat pumps (see Fig. 4) and potentially room air conditioners will dominate the next decade. A key challenge is reducing refrigeration demand to avoid capacity constraints from continued RACHP growth.

Demand minimization requires measures beyond low-GWP alternatives and high energy efficiency, which are the main Kigali Amendment focus areas (where energy efficiency is an added parameter not subject to compliance with the Amendment, given in Kigali Decision XXVIII/2, para 22).

ACTIONS AFFECTING DEMAND

The supply-side actions must be complemented by demand-side measures, including both active and passive strategies, with passive approaches expected to become

increasingly important. Improving efficiency and reducing heating and cooling demand will remain essential.

However, additional demand-side measures should also be considered, including: (1) significant behavior changes (2) the use of different (lower) temperature differences in operating refrigeration, AC, and heat pumps than used so far, (3) combining electricity from renewables and electricity and heat storage on a large and small scale, and lastly, but important (4) a wide range of passive measures, including site selection, architectural design, urban planning, and increased use of vegetation and trees in cities. The first decade after Kigali (2016-2026) focused primarily on HFC phase-down and RACHP efficiency. The next decade will require broader approaches for demand reduction, including lifestyle measures, advanced building cooling materials, passive strategies, and improved building design. Although beyond the Kigali Amendment's formal scope, integrating these measures with HFC phase-down strategies would further reduce refrigerant use, emissions, and energy consumption.

CONCLUSIONS

Over the last 10 years, Kigali has well-deserved its place in the transitioning of HFCs to low-GWP and near-zero GWP refrigerants. Some of the main conclusions include the following (but not limited to):

- Energy efficiency and demand reduction will be critical for Kigali progress (2026–2036), alongside HFC phase-down.
- Improving equipment efficiency

and reducing energy demand can lower fossil-fuel-related emissions and limit the need for additional renewable generation capacity.

- A key question is whether demand-reduction measures should be integrated into Kigali strategies or addressed through broader CO₂ reduction frameworks.

- Future discussions will need to assess the cost-effectiveness of demand-side measures compared with expanding electricity generation capacity.

- Rapid RACHP growth will increase demand for materials, refrigerants, manufacturing capacity, electricity generation, grid infrastructure, and critical minerals, creating supply-chain pressures and emission risks unless addressed through demand reduction, efficient designs, and alternative technologies.

- Rising incomes, urbanization, and increasing heat waves are expected to accelerate cooling demand and RACHP growth, increasing pressure on energy, materials, and manufacturing resources while making efficient design and passive demand-reduction measures increasingly important.

- As electricity grids may not be prepared for rapidly increasing RACHP demand, locally generated power and cost-effective demand-side solutions will become increasingly important; investment costs per kW for active and passive measures compared with renewable energy capacity will be a key determining factor.

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How Fast can we Defluorinate the HVAC/R Sector?



Armin Hafner

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Technology (NTNU)*

INTRODUCTION

In their studies, Lorentzen, Ciconkov, and Kauffeld & Dudita have emphasized earlier that achieving a sustainable refrigeration sector ultimately requires the elimination of synthetic refrigerants and the prevention of their emissions. Natural refrigerants have been used successfully in refrigeration and heat pump applications since the nineteenth century and provide nowadays again proven alternatives to fluorinated substances. Many synthetic refrigerants contribute to environmental burdens through their atmospheric degradation products, including PFAS-related compounds such as trifluoroacetic acid (TFA), which is highly persistent in the environment. Therefore, alongside the revised EU F-Gas Regulation and the Kigali Amendment to the Montreal Protocol, the proposed ECHA PFAS restriction is expected to further accelerate the phase-out of most synthetic refrigerants.

As highlighted by Arp et al., trifluoroacetic acid (TFA) has become the dominant PFAS in the environment, originating primarily from the atmospheric degradation of fluorinated gases and certain pesticides, Palm and Hart et al. similarly identify F-Gases as a major source of TFA formation. Arp et al. further warn that TFA may represent a 'planetary boundary threat for novel entities' because of its rapidly increasing global exposure. The societal costs of PFAS contamination are substantial, with water pollution recognized as a major concern by Ricardo and Trinomics. These concerns are supported by EU assessments, which identifies chemical contamination of surface water and groundwater as a significant risk to both human health

and aquatic ecosystems due to acute and chronic toxic effects. Data from River Basin Management Plans show that 46% of EU surface waters and 24% of groundwater bodies fail to meet existing environmental quality standards. In response, the Drinking Water Directive (DWD) strengthens protection against emerging contaminants and chemical mixtures, including PFAS-related substances. Therefore, the well-intentioned proposed EU PFAS restriction should be seen as the enabler for the required and possible transition away from F-Gases within the refrigeration and heat pumping sector. The availability of natural-refrigerant technologies allows the entire HVAC&R sector to deploy future-proof, energy-efficient systems with long-term regulatory compliance. Existing installations should be properly maintained and responsibly decommissioned to minimize environmental and health impacts. A significant challenge in the transition to sustainable & clean refrigeration and heat pump technologies is the limited information provided to end-users regarding the environmental and potential health implications of fluorinated refrigerants and their degradation products. As a result, purchasing decisions are often based primarily on current regulatory compliance, equipment cost, and low-GWP values, without a full understanding of the broader impacts associated with PFAS-related substances. Consequently, many owners have invested and still invest in systems using so-called low-GWP F-Gases that were promoted as long-term environmentally friendly solutions, only to face the prospect of replacement within a relatively short period due to emerging PFAS restrictions in the European Union. This lack of transparent information

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by the designers and vendors can lead to avoidable economic costs for end-users while prolonging emissions of persistent fluorinated substances to the local and global environment. Providing clear, mandatory, and balanced information on long-term environmental, health, and regulatory risks is therefore essential to support informed investment decisions and to avoid technology choices that may soon become obsolete and difficult to maintain. In the following chapter a brief overview of currently available clean technologies for the different application areas is provided.

The intention is to support decision makers to get offers for such technologies, whenever a new installation or a replacement must be ordered and becomes the asset and responsibility of the owner.

DEFLUORINTATED SYSTEM ALTERNATIVES

The system solutions described are a representative selection to cover the largest high-value and the largest volume segments within the HVAC & R sector, as well as some heat pump options.

Industrial & commercial chillers

There are a large capacity range of chillers in the market applying hydrocarbons as the working fluid. R290 (propane) became the preferred natural refrigerant for commercial and industrial chillers in Europe, due to the EU F-Gas phase-out and decarbonization policies.

The market is still fragmented, but a handful of manufacturers are emerging as leaders in medium and large-capacity R290 chiller applications. R290 chillers are primarily used in industrial process cooling, commercial building HVAC systems, and increasingly in data centres cooling units.

The largest capacity applications include food and beverage processing, plastics and chemical manufacturing, pharmaceutical facilities, shopping malls, office buildings, hospitals, hotels, and public infrastructure. Their popularity is driven by the high energy efficiency of R290, its ultra-low global warming

potential (GWP), and compliance with increasingly stringent EU F-Gas regulations. In recent years, adoption has grown particularly quickly in Germany, the Nordic countries, the Netherlands, France, and Italy, with data centres emerging as one of the fastest-growing markets for large-capacity chillers. There are also alternative solutions available for lower volume markets, as an example shown by De Zan et al., demonstrating a commercial type of an Air-to-Air rooftop unit for buildings like cinemas, applying R744.

Heat pump chillers

R744 (CO₂ - carbon dioxide) heat pump chillers applying carbon dioxide as a natural refrigerant often in a transcritical cycle. Compared with R290, R744 is non-flammable, and is particularly attractive where high hot water temperatures supplies (70-90°C+) are required or where strict safety requirements limit the use of hydrocarbons.

While R290 units are preferred in many commercial and industrial chiller installations, R744 heat pump chillers are increasingly selected for projects, designed with a low heat sink return temperature, as only R744 systems can provide an efficient high temperature lift, necessary when producing hot water in high performance buildings like hotels or gyms.

These double usage units are often applied in local and district energy systems, hotels, hospitals, and industrial sites, where safety, sustainability, and simultaneous heating/cooling are major drivers. The global availability and implementation of R744 heat pump chillers is not limited to Europe, America, and Far East. There are also several suppliers delivering these units successfully across India, in accordance with the local policy 'make in India'.

Variable Refrigerant Flow systems

These systems are characterized by a single outdoor unit connected to multiple indoor units, with the refrigerant flow continuously adjusted to each zone according to

heating or cooling demand. Several defluorinated alternative systems are emerging for these applications, particularly in larger commercial buildings. One leading OEM has already developed and deployed a R744 VRV system in several buildings and is able to prepare for broader market adoption as regulatory requirements and customer demand evolve. Another alternative is a water-based distribution loop within the building, connected to a central heat pump-chiller using either R744, R290, or even R717 (ammonia) as the refrigerant. Given the growing shortage of qualified refrigeration technicians able to install all required units, closer cooperation with the hydronic / plumber sector could help overcome this bottleneck.

Such an approach may also accelerate the transition from fossil fuel-based heating systems to heat pump technologies by leveraging existing competencies in the plumbing and hydronic installation trades.

Split Air Conditioning units

The market share of R290 split air-conditioning units is still in the low single-digit percentage range, but it is expanding. Most commercially available units are in the range of 2.5 – 5 kW residential and light-commercial segment, where the required refrigerant charge is typically limited to only a few hundred grams per unit. Commercial products are already available from the main global manufacturers, while other major OEMs, are now introducing propane-based air-conditioning products.

Although R290 systems currently account for only a small share of global split AC sales, their adoption is expected to accelerate, particularly in Europe, driven by the shortage of R32 because of the F-Gas regulations and repeating heat waves. Also in this business section, the availability of qualified personnel is increasingly becoming one of the main barriers to the rapid deployment of R290-based air conditioning and heat pump systems. While the technology is commercially available and has already been deployed in millions of



Figure 1: R744 Chiller for ship cooling application, $Q_o=100$ kW, Chilled water 12°C to 7°C , seawater temperatures up to 36°C .



Figure 2: R744 Industrial heat pump chiller unit. 120 kW hot water production, lifting from 27°C to 90°C . Chilled water 12°C to 7°C .

units worldwide, R290 is classified as a flammable refrigerant and therefore requires additional competencies related to installation, commissioning, leak testing, servicing, and risk assessments. Similar challenges have already been observed during the transition from R410A to R32 systems, where shortages of trained technicians slowed market adoption in several regions. As the market must defluorinate, the need for training and certification is expected to grow faster than the available workforce. Consequently, workforce development may become a more significant constraint than technology availability or manufacturing capacity.

Supermarket refrigeration

New commercial supermarket refrigeration systems are increasingly based on R744, provided that local suppliers and service organizations have the expertise required for installation and maintenance. For medium and large stores, centralized R744 systems offer the highest energy efficiency while eliminating the need for numerous stand-alone cabinets that release heat directly into the sales area. Through effective heat recovery, these systems can provide space heating, domestic hot water, and in some cases even air conditioning, significantly reducing or eliminating the need for auxiliary heating & AC equipment.

Modern R744 supermarket systems are therefore evolving into integrated energy centers that combine refrigeration, heating, cooling, and thermal storage within a single platform. In regions with suitable

infrastructure, surplus heat can even be exported to neighboring buildings or district heating networks, enabling supermarkets to become net suppliers of thermal energy. Continued advances in ejector technology and heat recovery have further improved system efficiency, making R744 refrigeration one of the most mature, total cost efficient, and successful natural refrigerant technologies in commercial applications. For smaller stores, stand-alone or water-loop systems using R 290 are often an attractive and cost efficient alternative due to their simpler installation as store lifetime is often limited.

Mobile- & Transport refrigeration

Mobile and transport applications are an important growth area for applying natural refrigerants. In the automotive sector, a leading German car manufacture has announced its intention to convert all battery-electric vehicle heat pumps and air-conditioning systems to R744 by 2030 and has experience with more than 1 million vehicles equipped with R744 heat pumps in operation. In railway applications, propane (R290) has proven to be a technically and economically viable alternative to conventional refrigerants.

Deutsche Bahn is deploying R290 HVAC systems in both regional and high-speed trains and expecting wider adoption across Europe. In transport refrigeration, natural refrigerants are also present, with R744 applied in refrigerated containers and specialized transport systems, while innovative truck

and trailer refrigeration solutions are based on CO_2 (as an indirect working fluid) and hydrocarbons such as R1270 (propylene) are on the road. Together, these examples demonstrate that natural refrigerants are no longer limited to stationary refrigeration and heat pump systems but are rapidly expanding into mobile air-conditioning, thermal management, and transport refrigeration applications.

Hot water heat pump

One of the most successful examples of natural refrigerant technology so far is Japan's Eco Cute program, which uses R744 heat pumps for domestic hot water production. Introduced in 2001, the technology has been adopted by all major Japanese manufacturers and surpassed 10 million cumulative domestic shipments in March 2025. Eco Cute systems demonstrate that R744 heat pumps can be deployed at large scale while delivering high energy efficiency and long-term regulatory compliance. In addition to providing domestic hot water, these systems increasingly support renewable electricity integration through thermal energy storage and demand-response operation.

Light commercial units

One of the earliest large-scale deployments of natural refrigerants was achieved through the Refrigerants, Naturally! initiative, led by Coca-Cola, PepsiCo, Unilever, Red Bull, and other global consumer brands.

The initiative focused on beverage

coolers, vending machines, ice cream freezers, and other point-of-sale refrigeration equipment. By the end of 2017, more than 7.25 million natural refrigerant units had been installed worldwide, avoided by that time already 43.5 million tonnes of CO₂-equivalent emissions. Since then, major beverage and food companies have continued replacing HFC-based equipment with predominantly R-290-based systems. While a consolidated global figure is not publicly available, the installed base is widely believed to have exceeded 10 million units worldwide, making light-commercial refrigeration, beside the Japanese Eco Cutes, a significant market for natural refrigerant units.

Medical- and Pharma Refrigeration

Medical and pharmaceutical ultra-low-temperature refrigeration has historically relied on high-GWP refrigerants such as R23 to achieve storage temperatures down to -80°C and below. However, the revised EU F-Gas Regulation will effectively phase out the use of these refrigerants in many applications after 2030, accelerating the transition towards natural refrigerant alternatives. Current developments focus on hydrocarbon cascade systems using R170 (ethane), R290, R1150 (ethylene), and R1270, as well as air-cycle refrigeration technologies. Studies indicate that R170/R290 cascade systems can efficiently achieve storage temperatures between -70°C and -86°C, making them suitable for pharmaceutical products, vaccines, biological samples, blood products, cells, and gene therapies.

Air-cycle refrigeration is also widely applied for pharmaceutical and medical ultra-low-temperature applications. Several OEMs of air compressors and entire units are supplying the market. These systems apply reverse Brayton cycle technology using air as the only working fluid, thereby eliminating concerns related to refrigerant phase-down regulations, PFAS, toxicity, and flammability.

Air-cycle refrigeration is increasingly

considered a viable option for freeze-drying, vaccine storage, plasma freezing, and other biomedical applications requiring temperatures between approximately -40°C to -80°C and below. In addition to hydrocarbon- and air-cycle-based ultra-low-temperature technologies, R784 (krypton) has recently been investigated as a natural refrigerant for applications requiring temperatures below the operating range of CO₂ systems. Contiero et al. proposed ejector-supported krypton refrigeration cycles for future CERN detector cooling systems, demonstrating the potential of R784 as a non-flammable natural refrigerant for specialized ultra-low-temperature applications below -60°C, also applicable for medical- and pharma refrigeration units.

CONCLUSION

The refrigeration, AC, and heat pump sectors are entering a decisive phase in the transition away from fluorinated refrigerants. While the Kigali Amendment and the revised EU F-Gas Regulation have already accelerated the reduction of high-GWP refrigerants, growing concerns regarding PFAS emissions and the formation of persistent degradation products such as trifluoroacetic acid (TFA) further strengthen the case for a complete defluorination of the sector. The environmental and societal costs associated with PFAS contamination increasingly challenge the continued use of fluorinated working fluids, even where their direct climate impact has been reduced through lower-GWP alternatives.

The examples presented in this contribution demonstrate that natural refrigerants are no longer niche technologies. Proven and commercially available solutions based on R290, R744, R717, hydrocarbons, air, and other natural working fluids are already deployed successfully across virtually all major application areas, including industrial chillers, heat pumps, air conditioning, supermarket refrigeration, transport cooling, domestic hot water production,

light-commercial refrigeration, and ultra-low-temperature medical applications. Several of these sectors have achieved deployment volumes measured in millions of installations worldwide, confirming both technical maturity and market acceptance. The main obstacles to broader implementation are therefore no longer related to technology readiness. Instead, barriers increasingly arise from insufficient awareness among end-users, limited availability of trained personnel, fragmented procurement practices, and continued market acceptance of fluorinated technologies that may soon face additional regulatory restrictions. The shortage of qualified HVAC&R technicians capable of designing, installing, and maintaining systems is emerging as one of the most significant challenges for the coming decade. Expanding vocational training, continuing education, and recruitment of young professionals into the sector should therefore be viewed as an essential component of climate and energy policy. To support informed investment decisions, greater transparency regarding refrigerant-related environmental, health, and regulatory risks is needed. System owners should be provided with clear information on the long-term implications of refrigerant choices, enabling them to evaluate not only current compliance but also future regulatory and environmental liabilities. A mandatory declaration acknowledging refrigerant-related risks could be one mechanism to strengthen transparency and accelerate market transformation. Ultimately, the evidence suggests that a future-proof HVAC&R sector can be built entirely on natural working fluids.

The required technologies exist, their performance has been proven, and successful deployment is already taking place at global scale. The remaining question is therefore no longer whether defluorination is technically possible, but how quickly industry, policymakers, and end-users are willing to implement solutions that are already available today.

Accelerating Progress in the Cooling Sector: UNEP OzonAction's Global Momentum on Gender



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ABSTRACT

This paper highlights UNEP OzonAction's efforts to advance gender and youth inclusion in the refrigeration and air-conditioning (RAC) sector as part of the global transition to sustainable cooling under the Montreal Protocol and the Kigali Amendment. It showcases initiatives across regions, including a Caribbean pathway to boost youth participation in the sector, Zimbabwe's evidence-based gender action plan, and targeted training programmes for female professionals in Africa and South Asia.

These initiatives address key barriers such as limited access to training, stereotypes and biases, and underrepresentation in leadership. A strong emphasis is placed on skills development, mentorship, and inclusive policies to empower women and young professionals.

The International Network of Women in Cooling (INWIC) further strengthens global collaboration through mentorship and knowledge exchange. Overall, the paper demonstrates that coordinated, gender-responsive approaches are essential to building a diverse, skilled workforce and achieving climate-friendly cooling transitions.

INTRODUCTION

Across the globe, the refrigeration and air-conditioning (RAC) sector is playing an increasingly vital role in advancing climate action and sustainable development. As countries transition towards energy-efficient and climate-friendly cooling solutions, there is a growing recognition that a diverse workforce is essential to meet emerging demands. Through initiatives spanning youth engagement, gender-responsive

policies, technical training, and global mentorship through INWIC, UNEP OzonAction is supporting countries and partners to empower women and young professionals, ensuring that the future of cooling is not only sustainable, but fair and opportunity-driven.

CARIBBEAN YOUTH PATHWAY: BUILDING THE NEXT GENERATION OF COOLING PROFESSIONALS

The Caribbean is taking decisive steps to empower a new generation of skilled technicians through a structured Pathway to Increase Youth Participation in the Refrigeration Servicing Sector (RSS). Developed following regional consultations in Belize and Grenada, the initiative responds to growing demand for skilled labour in sustainable cooling while addressing youth unemployment and gender gaps in technical professions.

At its core, the pathway adopts a comprehensive framework spanning six key areas: awareness, education, gender inclusion, industry engagement, youth networks, and policy support. This multi-stakeholder approach reflects the understanding that transforming the refrigeration and air-conditioning (RAC) sector requires coordinated action across governments, training institutions, industry actors, and youth themselves.

Efforts to improve awareness focus on showcasing RAC careers as attractive, future-oriented opportunities.

Campaigns featuring young technicians, including women, are complemented by school outreach, career fairs, and skills competitions aligned with global events such as World Youth Skills Day.

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Figure 1: The Caribbean pathway promotes youth participation in refrigeration through awareness, training, and gender inclusion initiatives. It emphasizes TVET expansion, mentorship, and private-sector engagement to create opportunities for young professionals.

These initiatives aim to shift perceptions and highlight the sector's income potential, technological innovation, and role in climate action. Access to training and certification remains another central pillar. The pathway emphasizes expanding technical and vocational education and training (TVET), introducing blended learning models, and offering scholarships, particularly for women. Such measures are designed to reduce entry barriers and ensure that youth from underserved communities

can participate in the sector. Importantly, gender is embedded throughout the pathway. Proposed actions include workplace policies addressing harassment and pay equity, mentorship programmes, and the promotion of female role models. This reflects a growing recognition that achieving sustainable cooling transitions depends on unlocking the full potential of women and youth. Private sector engagement is also key. Companies are encouraged to provide internships and

apprenticeships while governments should integrate inclusive language in procurement processes to support youth- and women-led businesses. At the same time, youth networks and digital communities should be strengthened to foster peer learning and regional exchange. By combining policy, education, and social change, the Caribbean pathway offers a replicable model for building a diverse, future-ready workforce, ensuring that young people, especially women, can actively contribute to climate-friendly cooling solutions.

ZIMBABWE: EVIDENCE-BASED ACTION FOR GENDER EQUALITY IN COOLING

Zimbabwe has emerged as a leader in advancing gender equality in the cooling sector through a national survey, targeted workshops, and a draft action plan that together form a robust, evidence-based approach to reform.

The National Survey on Women in Cooling provides critical insights into the realities faced by female professionals in the RACHP sector. With 95 respondents nationwide, the study reveals a young workforce, with 44% under 30, largely engaged in technical hands-on roles such as servicing and maintenance.

Despite their technical engagement, women remain underrepresented in leadership positions, with only 11% identifying as business owners and very few in managerial or academic roles.

This highlights structural barriers that limit career progression and influence.

The survey also identifies persistent challenges:

- Limited access to career advancement opportunities
- Gender pay gaps, with 65% perceiving lower salaries than men
- Restricted access to training, tools, and funding
- Workplace discrimination and inadequate facilities

Nevertheless, the findings also reveal strong motivation and resilience. Many women are driven by the technical nature of the work,

environmental impact, and the opportunity to contribute to climate protection. Notably, 64% reported having access to mentorship, underscoring the importance of support networks.

Building on these insights, a national workshop for female technicians facilitated the development of a draft action plan addressing gender-based challenges. Key recommendations include:

- Integrating gender quotas and anti-harassment policies in companies
- Expanding training opportunities and providing tools for women technicians
- Promoting entrepreneurship and supporting women-owned SMEs
- Enhancing awareness campaigns and stakeholder engagement
- Strengthening collaboration between government ministries and industry associations

The action plan also emphasizes behavioural change across all stakeholders - from empowering women practitioners to encouraging male allies and strengthening institutional responses through inclusive policies and enforcement mechanisms.

Together, the survey, workshop,

and action plan represent a comprehensive approach that moves beyond diagnosis to actionable solutions - positioning Zimbabwe as a model for gender-responsive programming in the cooling sector.

TRAINING WOMEN PROFESSIONALS ACROSS AFRICA AND SOUTH ASIA

Across Africa and South Asia, UNEP OzonAction is accelerating efforts to empower women through targeted training programmes and Training-of-Trainers (ToT) initiatives, ensuring that female professionals can access high-quality skills development and leadership opportunities.

In Anglophone Africa, regional training initiatives have focused on strengthening technical competencies while fostering collaboration among women technicians.

Participants have received hands-on training in environmentally friendly refrigeration practices, safety standards, and new technologies, equipping them to meet evolving market demands and contribute to climate goals.

Similarly, a regional workshop

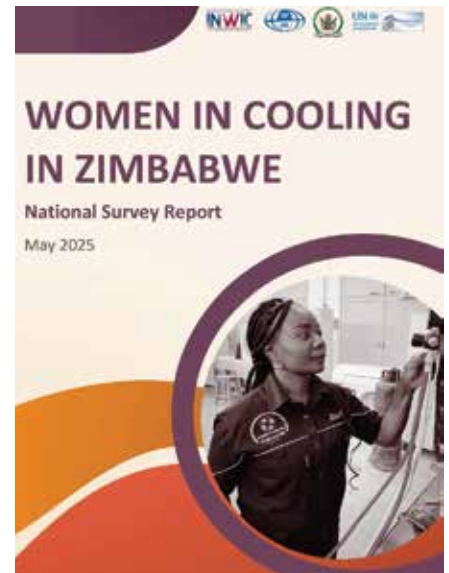


Figure 2: Zimbabwe's national survey highlights barriers faced by women, including pay gaps and limited advancement.

in Dakar for Francophone Africa brought together female technicians to build technical skills and create peer support networks.

These trainings not only enhance technical expertise but also create safe spaces for women to share experiences and address common challenges, such as workplace discrimination and limited access to opportunities.



Figure 3: Regional trainings in Africa and South Asia improve skills and leadership of female technicians. Training-of-trainers programmes ensure sustainability and expand impact across regions.

In parallel, South Asia has prioritized a Training-of-Trainers (ToT) approach, recognizing the multiplier effect of empowering female trainers and assessors. Through UNEP - ATF training programme, women have been equipped to deliver certified training and mentor the next generation of technicians. This approach ensures sustainability by embedding gender inclusion within national training systems and institutions.

Across these regions, several common themes emerge:

- Skills development as an entry point to empowerment
- Networking and peer support as critical enablers
- Leadership development through ToT programmes
- Integration of gender considerations into technical training systems

These initiatives demonstrate that investing in women's technical skills not only addresses labour shortages but also improves service quality, innovation, and environmental outcomes.

By strengthening women's roles as technicians, trainers, and leaders, UNEP OzonAction is helping to transform the cooling sector into a more resilient industry.

THE INWIC MENTORSHIP PROGRAMME: CONNECTING WOMEN GLOBALLY

The International Network of Women in Cooling (INWIC) is a global platform dedicated to strengthening the participation, visibility, and leadership of women across the refrigeration and air-conditioning sector. UNEP OzonAction is one of the 13 founding partners of INWIC and plays a key role in supporting its activities by facilitating collaboration, knowledge exchange, and capacity-building initiatives that empower women and expand their opportunities in sustainable cooling industries.

Mentorship has emerged as a powerful tool for addressing many of the barriers identified across regions, from lack of career guidance to limited networking opportunities. The INWIC mentorship programme

connects experienced professionals with early-career women, fostering knowledge transfer, confidence-building, and professional growth. Currently, there are around 80 participants in the programme, and around 20 on-going mentor-mentee relationships.

Survey data from Zimbabwe underscores the importance of mentorship, with 64% of respondents reporting having benefited from mentoring support. This aligns with global evidence that mentorship enhances career progression, retention, and leadership development for women in technical fields.

The INWIC initiative goes beyond one-on-one mentoring by creating a global community of practice. Through virtual platforms, workshops, and networking events, participants can share experiences, exchange technical knowledge, and build professional relationships across borders.

Key objectives of the programme include:

- Strengthening leadership capacity among women in cooling
- Expanding professional networks and visibility
 - Promoting knowledge exchange and best practices
 - Supporting career advancement and entrepreneurship

Importantly, the programme

complements national and regional initiatives, such as those in Zimbabwe and the Caribbean, by providing a global dimension to gender empowerment efforts.

CONCLUSION

From the Caribbean's youth-focused pathway to Zimbabwe's evidence-based reforms, and from regional training programmes in Africa and South Asia to global mentorship through INWIC, UNEP OzonAction is advancing a comprehensive and interconnected approach to equal opportunities in the cooling sector.

These initiatives demonstrate that meaningful change requires more than isolated interventions.

It demands coordinated action across education, policy, industry, and community level, combined with sustained investment in women's skills and visibility.

As countries continue to implement the Montreal Protocol and the Kigali Amendment and transition towards climate-friendly cooling solutions, ensuring the full participation of women and youth will be essential. By viewing its programmes through a gender lens, UNEP OzonAction is ensuring more inclusive outcomes and improving the effectiveness and sustainability of environmental efforts.

INWIC MENTORSHIP PROGRAMME

The INWIC Mentorship Programme connects women professionals in the cooling sector worldwide

- Share knowledge and experience**
Exchange practical insights and learn from each other's professional experiences.
- Build meaningful connections**
Connect one-to-one with another woman in the cooling sector and expand your professional network.
- Grow together**
Develop new perspectives, skills and confidence while supporting each other's professional growth.

FREE for INWIC Members

LEARN MORE
Discover the INWIC Mentorship Programme

JOIN INWIC
Become a member and benefit from the mentorship programme and many more!

Kigali, Ten Years Later: a Review of the Energy Transition and Future Challenges for Global Cooling



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ABSTRACT

Ten years after the adoption of the Kigali Amendment for the gradual reduction of hydrofluorocarbons (HFCs), the article analyses the results and future prospects of the refrigerant transition in the cooling sector, comparing the situation of the European market with that of international and emerging markets. Although Europe has benefited from an initial technological advantage thanks to early regulations, maintaining global leadership requires constant innovation and the ability to adapt to foreign regulatory environments that are still under development.

The analysis highlights that the mere substitution of traditional refrigerants with low-GWP alternatives is no longer sufficient on its own; climate success crucially depends on the energy efficiency of the systems and the decarbonisation of electricity production in the face of rapidly growing demand. Finally, the main bottlenecks of the transition are identified: the need to harmonise safety standards and the urgent need to train qualified technicians capable of managing the new refrigerants.

ARTICLE

Ten years after the adoption of the Kigali Amendment to the Montreal Protocol on 15 October 2016, the global cooling sector stands at a decisive moment. The agreement, designed to phase down hydrofluorocarbons (HFCs), marked one of the most significant international climate commitments of the last decade.

Unlike the Montreal Protocol itself, which successfully addressed ozone-depleting substances, Kigali focuses on reducing high-global warming

potential (GWP) refrigerants while maintaining the rapid expansion of cooling services worldwide.

A decade later, the transition has unquestionably begun, but it has also become increasingly clear that replacing one refrigerant with another is only one part of a much larger transformation. Refrigerants remain important because they directly affect greenhouse gas emissions through leaks and end-of-life losses. However, indirect emissions generated by the electricity consumed throughout the lifetime of cooling equipment are becoming the dominant environmental challenge. As demand for air conditioning, refrigeration, data centres and cold-chain infrastructure accelerates, the success of the Kigali Amendment will depend as much on energy efficiency and electricity decarbonisation as on the refrigerants themselves.

Europe entered this transition with a significant advantage thanks to the early implementation of the F-Gas Regulation. Yet maintaining this leadership in an increasingly competitive global market is far from guaranteed. Meanwhile, many emerging economies are only beginning to establish the regulatory frameworks, technical standards and professional skills required to support the transition. These contrasting realities illustrate that Kigali is progressing at different speeds across the world, reflecting differences in economic development, regulatory maturity and energy infrastructure.

Europe's early leadership

European manufacturers were among the first to respond to increasingly stringent fluorinated gas legislation. Long before Kigali entered into force internationally, European companies had already invested

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heavily in developing alternative refrigerants, redesigning equipment, improving energy efficiency and adapting manufacturing processes to comply with progressively tighter environmental requirements.

This early regulatory pressure created an important technological advantage. European manufacturers accumulated experience in designing systems using low-GWP refrigerants, while simultaneously improving product performance and reliability. As a result, Europe today possesses one of the world's most mature portfolios of commercially available low-GWP technologies.

However, technological leadership cannot be viewed as permanent. Continuous innovation remains essential because regulatory compliance alone does not guarantee long-term competitiveness. Manufacturers must continue investing in research, product development and production capabilities if Europe is to retain its position in global markets.

At the same time, Europe's increasingly ambitious regulations introduce new competitive challenges.

The export restrictions introduced under Regulation (EU) 2024/573 for several categories of equipment containing high-GWP refrigerants limit the ability of European manufacturers to supply products

to countries whose regulatory frameworks are still evolving. Many emerging markets have not yet reached the stage where low-GWP alternatives can be rapidly adopted across all applications.

This creates an important strategic dilemma.

While European industry has developed advanced technologies, reduced commercial presence in developing markets could weaken its long-term influence. If competitors from other regions establish stronger market positions during this transitional period, the technological gap that Europe currently enjoys may gradually narrow.

Maintaining leadership therefore requires not only technological innovation but also continued engagement with international markets as they progressively implement Kigali commitments.

The global transition proceeds at different speeds

One of the defining characteristics of the Kigali Amendment is that implementation varies considerably between countries. Europe entered the transition with an established regulatory framework, experienced manufacturers and qualified technical personnel.

In contrast, many countries across Asia, Africa and the Middle East have only recently begun introducing the

legislation and institutional structures necessary to support the phase-down of HFCs.

This difference in timing should not necessarily be interpreted as failure. Countries face very different economic conditions, infrastructure limitations and policy priorities. Building an effective ecosystem for refrigerant transition requires far more than legislation alone.

Professional qualifications, technical standards, certification schemes, enforcement mechanisms and market surveillance all need to develop simultaneously.

Many emerging economies therefore face a transition that extends well beyond refrigerants themselves. Establishing vocational training systems, updating building regulations, introducing safety standards and educating installers may require several years before low-GWP technologies can be deployed at scale.

Rather than attempting to replicate Europe's timetable, many countries are adopting a gradual approach that reflects their own institutional capacity.

This slower implementation may ultimately prove beneficial. Nations beginning the transition today can learn from the experiences, technical challenges and regulatory adjustments already encountered by early adopters, avoiding many of

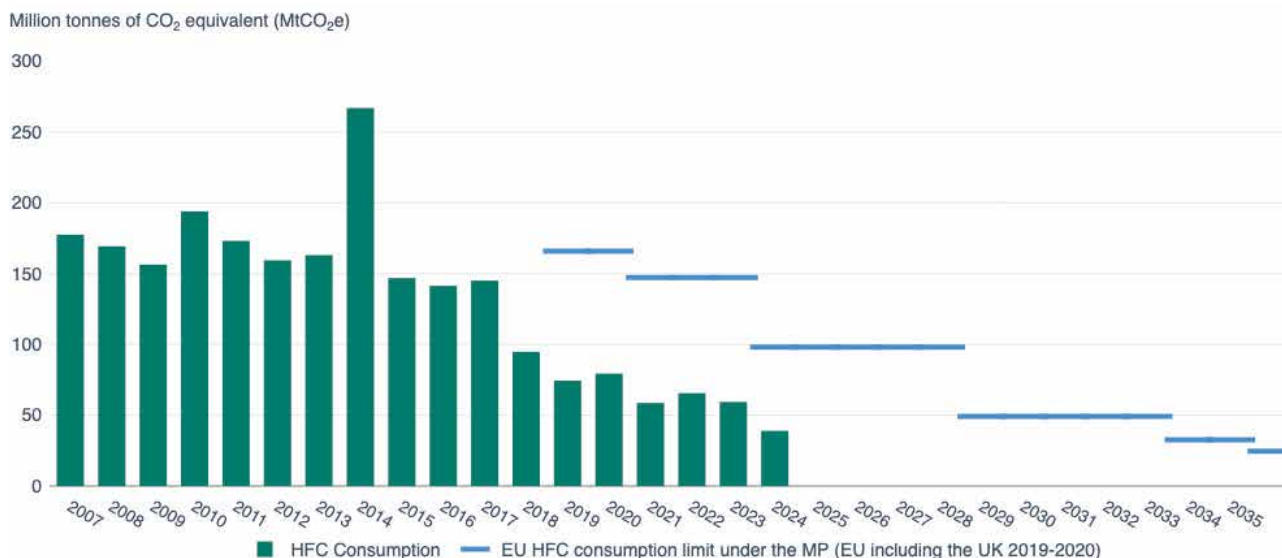


Figure 1: EU contribution to the global phase-down of HFCs under the Kigali Amendment to the Montreal Protocol, which introduces limits to the consumption of HFCs, starting in 2019. SOURCE: European Environment Agency (EEA)
HFC: hydrofluorocarbon - MP: Montreal Protocol - Mt: million tonnes

the mistakes made during Europe's initial transition.

Refrigerants alone will not deliver climate success

Perhaps the most important lesson emerging after ten years of Kigali is that refrigerant replacement alone cannot achieve climate neutrality in the cooling sector.

Refrigerant policy must increasingly be integrated within a broader energy transition strategy. Energy-efficient equipment reduces electricity demand throughout the operating lifetime of cooling systems, lowering both operating costs and greenhouse gas emissions. Simultaneously, decarbonising electricity generation ensures that the remaining electricity consumption carries a progressively smaller environmental footprint.

The challenge extends across virtually every sector relying on cooling technologies. Buildings require increasingly efficient air conditioning systems to cope with rising temperatures.

Data centres demand reliable cooling solutions as digitalisation expands worldwide. Food cold chains are becoming indispensable for reducing food losses and ensuring food security, particularly in developing countries. Healthcare systems similarly depend upon reliable refrigeration for medicines and vaccines. Viewed collectively, these sectors demonstrate that the environmental impact of cooling can no longer be assessed solely through refrigerant choice. Instead, cooling must be considered as part of an integrated energy system where equipment efficiency, electricity generation and system design all contribute to overall sustainability.

Energy efficiency becomes the central priority

The growing importance of energy efficiency extends well beyond environmental considerations. For many countries, particularly those where electricity prices are subsidised, inefficient cooling systems impose substantial financial burdens on public budgets. Every kilowatt-hour saved through improved refrigeration efficiency represents

electricity that governments do not need to generate, import or subsidise. Reduced electricity demand also lowers pressure on transmission networks, delays investments in additional generation capacity and improves overall energy security.

This broader perspective fundamentally changes the interpretation of Kigali. Rather than viewing the agreement solely as an environmental treaty targeting refrigerants, it increasingly becomes part of a wider strategy encompassing industrial development, energy planning and economic resilience. Nevertheless, energy efficiency alone cannot solve the problem.

Demand for cooling is expected to increase so rapidly over the coming decades that efficiency improvements, although substantial, will not completely offset rising electricity consumption.

Population growth, urbanisation and climate change are simultaneously increasing the number of cooling systems installed worldwide. Consequently, the ultimate success of global cooling depends upon the parallel decarbonisation of electricity production. Without cleaner power generation, indirect emissions will continue to dominate the sector's climate impact regardless of improvements in refrigerant technology.

Systems matter more than individual components

Another major lesson emerging during the Kigali transition is that system performance matters more than the performance of individual products. There is currently no universal refrigerant capable of optimally serving every application. Natural refrigerants, HFOs, HFC blends and other alternatives each present advantages and limitations depending on operating conditions, safety requirements, efficiency targets and application characteristics.

Similarly, highly efficient equipment does not automatically produce highly efficient systems. A premium chiller installed within a poorly designed hydraulic network may operate far below its theoretical

performance. Incorrect sizing, inadequate commissioning, poor maintenance or inappropriate control strategies can significantly reduce efficiency throughout the equipment lifetime. This system-based perspective shifts attention from individual products towards the entire cooling value chain. Designers, consultants, installers, commissioning engineers, maintenance technicians and building operators all influence final energy performance. Consequently, substantial opportunities remain for reducing energy consumption without requiring revolutionary technological breakthroughs. Better engineering practice, improved commissioning procedures and higher professional standards can often deliver significant efficiency gains using technologies already available today.

Safety standards and workforce development

The widespread adoption of low-GWP refrigerants introduces new technical challenges because many alternatives possess different safety characteristics from traditional HFCs. Several widely adopted refrigerants now fall within the A2L or A3 safety classifications, requiring new approaches to equipment design, installation and maintenance.

International standards such as EN 378 and IEC 60335 provide an essential technical framework for safely applying these refrigerants. However, standards alone cannot ensure safe implementation.

The limiting factor increasingly lies in workforce competence. Engineers and technicians must manage appropriate installation practices, leak prevention, commissioning procedures and maintenance requirements. Without adequate training, even well-designed systems may present unnecessary operational risks or fail to achieve expected performance.

This skills challenge is particularly acute in emerging economies where vocational education systems are still adapting to new technologies. Developing comprehensive

professional training programmes requires considerable institutional investment. Certification schemes, legal responsibilities, educational curricula and practical training facilities must evolve together. Professionalising the refrigeration and air conditioning workforce therefore represents one of the most important long-term investments supporting Kigali implementation. Well-trained technicians improve safety, maximise system efficiency, reduce refrigerant leakage and enhance equipment reliability throughout its operational life.

Harmonising regulations

Closely linked to workforce development is the need for greater harmonisation of safety regulations and building codes. Although international technical standards increasingly converge, important differences remain between national regulations governing building design, refrigerant charge limits and installation requirements. These inconsistencies complicate product development for manufacturers operating internationally while slowing technology transfer across markets. Greater harmonisation would reduce regulatory uncertainty, facilitate international trade and accelerate the global adoption of low-GWP technologies. Harmonised rules also simplify technician training by reducing differences between national requirements. Building codes deserve particular attention because they determine where and how certain refrigerants may be safely used. Updating these regulations often requires close cooperation between governments, standards organisations, manufacturers and the construction sector.

Why Kigali differs from Montreal

Comparisons between the Kigali Amendment and the original Montreal Protocol are inevitable, yet the two transitions differ fundamentally. The Montreal Protocol achieved remarkably rapid success because many substitute refrigerants possessed characteristics similar to the chemicals they replaced. Existing equipment designs required

relatively limited modification, and technicians could continue working using familiar installation practices. Kigali presents a far more complex technological transition. Low-GWP refrigerants frequently require redesigned equipment, modified safety procedures, updated standards and significantly expanded workforce training. Entire supply chains must adapt rather than simply substitute one refrigerant for another. For this reason, Kigali should not be expected to replicate the implementation speed achieved under the Montreal Protocol. The transition remains fully achievable, but its complexity inevitably requires more time.

Looking ahead

Ten years after its adoption, the Kigali Amendment has successfully established a common global direction for refrigerant transition. Technological progress has been substantial, regulatory frameworks continue to expand and an increasing number of countries are actively implementing their commitments. Yet the next decade will likely determine whether Kigali achieves its broader climate objectives. The refrigerant transition must increasingly be integrated with improvements in energy efficiency, workforce development, regulatory harmonisation and electricity decarbonisation. Europe retains important technological strengths but cannot assume that early leadership

will automatically continue. Continuous innovation and sustained international engagement remain essential if European manufacturers are to preserve their competitive position as emerging markets mature. At the same time, developing economies face the challenge of building the institutional foundations necessary for long-term success. Regulations, standards, vocational education and market development must evolve together if low-GWP technologies are to deliver their full environmental benefits. Ultimately, the central lesson after ten years is that the future of sustainable cooling extends far beyond refrigerants themselves.

Refrigerant choice remains an essential component of climate policy, but it is no longer sufficient on its own. The decisive factors will increasingly be the efficiency of cooling systems, the competence of the professionals who design and maintain them, and the ability of countries to produce low-carbon electricity capable of supporting the billions of cooling systems that will be installed over the coming decades. In this broader context, Kigali should be viewed not as the final destination but as the starting point of a much wider transformation. The environmental success of global cooling will ultimately depend on integrating refrigerant innovation with an equally ambitious transition of energy systems, technical skills and regulatory frameworks worldwide.



Building skills for a more sustainable future: Eurovent Middle East launched its HVACR Leadership Academy in October 2023, establishing a training initiative in Dubai to support the professional development of technicians and engineers across the Middle East. Through a cooperation agreement with Centro Studi Galileo, the Academy brings international training expertise to the region, offering certified technical courses and knowledge development programmes covering HVACR technologies, standards and best practices.

Regulatory Certainty and the Refrigerant Transition: Preserving Affordability, Sustainability, and Innovation



Stephen Yurek

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The ongoing, global transition to lower-global warming potential (GWP) refrigerants has been one of the most significant environmental and technological transformations in the history of the HVACR and water heating industry. In the United States, this transition has been driven in large part by a combination of innovation, investment, and a carefully constructed regulatory framework established through the American Innovation and Manufacturing (AIM) Act, which implements the objectives of the Kigali Amendment to the Montreal Protocol.

For manufacturers, distributors, contractors, and other industry stakeholders, the transition has required substantial planning and investment. Companies have redesigned products, retooled manufacturing facilities, trained employees, and educated customers. These investments were made with the expectation that the regulatory framework governing the transition would remain predictable and consistent – an expectation that has recently been tested by the U.S. Environmental Protection Agency's (EPA) rollback of the compliance requirements and deadlines of the Technology Transitions (TT) Program.

Over the past decade, the United States has experienced dramatic political shifts that have produced equally dramatic changes in Administration regulatory priorities. At AHRI, we refer to this phenomenon as “policy whiplash.”

Each presidential administration brings with it a new governing philosophy, a new cabinet, and new leadership of federal agencies.

While changes in policy are expected during significant transitions of power, abrupt reversals of long-established regulatory frameworks create

uncertainty that can undermine both environmental progress and economic affordability. The ongoing refrigerant transition provides one of the clearest examples of the ripple effect that results when regulatory stability is challenged.

INDUSTRY'S LONG RECORD OF COMPLIANCE

The global HVACR and water heating industry, of which AHRI is a major part, is – and has always been – a source of energy efficient and affordable solutions to the world's growing indoor environment needs, whether they be air conditioning in the hotter climates of developing nations or more environmentally friendly cooling and heating solutions in developed nations and regions such as the United States and Europe. We are veterans of regulatory initiatives and have completed two global refrigerant transitions. The industry is adept at working with regulators to identify realistic goals and incorporate them into policy with attainable and affordable compliance.

There is perhaps no better example of bipartisanship and industry collaboration than the AIM Act. Passed with widespread support in 2020, the legislation established a national framework for the reduction and phasedown of hydrofluorocarbons (HFCs). While it sounds simple, it accomplished the rare feat of satisfying both environmental activists, who wanted to see a shift to more environmentally friendly refrigerants, and industry, which was given a timeline to design and introduce new, innovative products to the market.

As a result, the implementing regulations for the AIM Act enjoyed an extremely high level of compliance. The January 2025 and



Figure 1: The United States Capitol serves as the seat of Congress, where the “policy whiplash” phenomenon is often reflected in legislators’ priorities.



Figure 2: The HFC phasedown timeline found in the AIM Act implements the objectives of the Kigali Amendment to the Montreal Protocol.

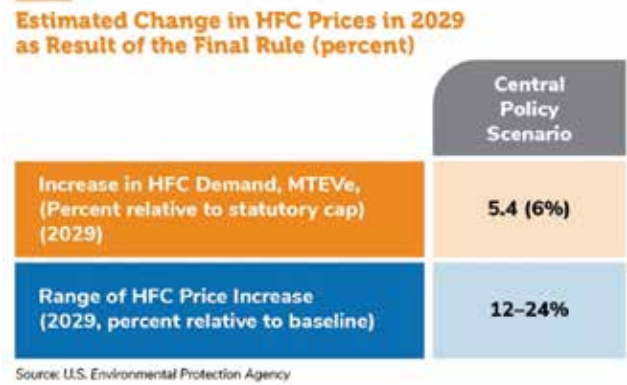


Figure 3: U.S. EPA analysis predicts an increase in refrigerant prices as soon as 2029.

January 2026 compliance deadlines came and went quietly, largely because much of the industry had started the transition well ahead of time. Today, all new residential and light commercial equipment uses the next-generation refrigerants required by law. It is important to point out that one of the most significant challenges in AIM Act compliance, the temporary shortage of cylinders to deliver R-454B refrigerant, was solved with patience, not policy. Upon identifying the problem, companies and distributors worked together to find solutions that minimized market disruption without compromising affordability or safety.

THE GROWING CHALLENGE OF REGULATORY INSTABILITY

The level of compliance described above is the result of confidence in the U.S. refrigerant transition within the manufacturing community. Following passage of the AIM Act, many companies invested millions of dollars in large-scale initiatives to ensure that their people, products, and production facilities would be prepared for the transition, with the understanding that those investments were protected by the long-term regulatory framework. With the U.S. EPA's rollback of some commercial refrigeration provisions of the original TT Rule, the industry now faces the challenge of how to restore that confidence. The TT reconsideration final rule injects a significant amount of uncertainty into the market. Production planning, workforce training, and capital

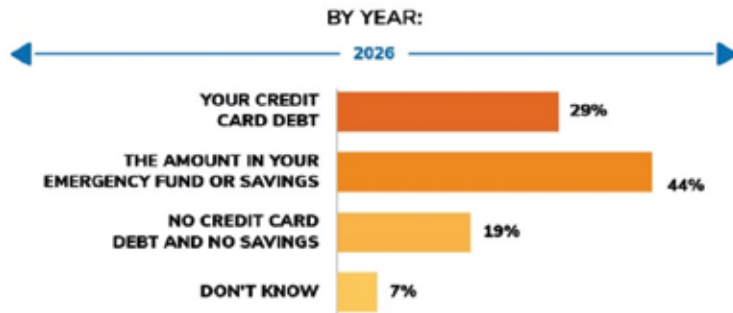
expenditures were developed around established compliance deadlines, some of which no longer exist. While the U.S. EPA argues that this rollback will reduce costs for working class families by lower prices at the grocery store, the reality is that it will likely continue to see food prices rise due to geopolitical events. The U.S. EPA's own analysis, released with the rule, acknowledged that delaying the transition could contribute to a 12- to 24-percent increase in refrigerant prices as soon as 2029. This, coupled with the delayed compliance deadline of January 1, 2032, for large commercial refrigeration systems, is likely to create a significant imbalance between the decreasing HFC supply and demand. By extending the commercial refrigeration compliance deadlines to 2032, the U.S. EPA is increasing the length of time that the market will demand these refrigerants, pushing their use well beyond the timeframe that refrigerant suppliers had planned under the AIM Act.

AFFORDABILITY DEPENDS ON PREDICTABILITY

In the wake of global economic challenges, countries around the world have seen a new policy focus on "affordability." In the United States, increased inflation spurred by higher gas and food prices has been a major focus of both political parties. Its continued rise in importance as a political issue reflects the fact that consumers, especially those considered middle class, are under a level of economic pressure that they

have not experienced for decades. Recent analysis from the Brookings Institution found that one third of American middle-class families no longer make enough money to afford basic necessities, such as food, housing, and childcare. The most recent data on personal income from the U.S. Bureau of Economic Analysis shows that, compared to 2025, American households are spending more, specifically on gas and energy, housing, and food, while saving at the lowest rate since 2022. Most concerning, according to Bankrate's Emergency Savings Report, about three in ten Americans have more credit card debt than emergency savings and more than half of Americans have the same or less money in savings than one year ago. That means that over time, these households are becoming less prepared for an emergency expense, not more. As we know, heating, cooling, and water heating are not luxuries, they are necessary to ensure human health, safety, productivity, and comfort, and the industry should support measures that make affordable, timely, and efficient repairs and replacements as accessible as possible. One of the best ways to make that happen is long-term regulatory stability, which allows businesses to confidently invest, early and often, knowing the future requirements of the market. Predictable implementation schedules allow manufacturers to invest in production capacity, address changes in their supply chains, and introduce new technologies at lower costs. This leads to a positive chain

We asked: Which is higher — your credit card debt or the money you have in your emergency fund or savings account?



Source: Bankrate Emergency Savings Survey Dec. 2-8, 2025

Figure 4: A recent survey from Bankrate found that roughly 3 in 10 Americans have more credit card debt than emergency savings.

of events for both manufacturers and consumers, as regulatory certainty encourages investment, investment drives innovation, innovation lowers costs, and consumers benefit from less expensive, more efficient equipment. When manufacturers are stymied in doing these things on a predictable schedule, many will be inclined to delay investments and increase contingency planning. These disruptions and their associated costs ultimately flow through distribution and installation chains and are reflected in the prices paid by consumers.

THE PATH FORWARD

The solution is not the elimination of existing regulations, which would create sliding goal posts that undermine investments and competition among manufacturers. The focus must instead shift to creating “smart regulation” that has clear objectives and reasonable compliance deadlines. Most important, smart regulations are those that remain in place long enough to allow an appropriate amount of time for the market and other stakeholders to respond. Smart regulations also recognize that environmental progress and economic growth are not mutually exclusive. The foundation of the current refrigerant transition serves as a promising example of how industry and government can work together to achieve meaningful environmental progress while supporting economic growth. The industry is following

a well-established roadmap that involves innovative technology, carefully planned investments, and workforce training. The remaining challenge is preserving the certainty necessary for success.

AHRI'S COMMITMENT TO AFFORDABILITY AND ENVIRONMENTAL STEWARDSHIP

AHRI remains ready to contribute to the needs of the HVACR and water heating industry through the current refrigerant transition.

To help plan for the future, AHRI's research department recently launched the Lower-GWP Alternative Refrigerants Evaluation Program (AREP), an industry wide collaborative effort to identify and evaluate promising alternative refrigerants for major product types, while avoiding duplicative efforts.

This is the third iteration of the program: AHRI successfully managed the original R-22 AREP in the 1990s and oversaw the work of AREP-2 in the 2010s in response to environmental concerns related to high-GWP refrigerants. As with previous efforts, AHRI will provide the leadership to coordinate and manage this industry-driven research and work closely with industry experts from its member companies. It is one of the best examples of the spirit of collaboration within the industry and exemplifies its commitment to innovation and improvement. AHRI hopes that the data collected from the AREP project will guide



Figure 5: AHRI is proud to begin the third iteration of the Alternative Refrigerants Evaluation Program (AREP-3).

future policy decisions by providing a clearer picture of the tangible benefits of new refrigerants and their applications. The HVACR industry has repeatedly demonstrated that it will meet ambitious policy goals when those policy goals are accompanied by realistic timelines that are economically justified and supported by regulatory certainty. The AIM Act and Kigali framework have provided that certainty and preserving it will be essential to maintaining momentum toward maximizing the use of lower-GWP refrigerants while protecting consumers. In the years ahead, the question will not be whether the industry can complete the refrigerant transition – we have proven time and again that innovation is well within our comfort zone. The question will instead become whether policymakers will provide the certainty necessary to allow American manufacturers and consumers to succeed.

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Toward Realistic and Sustainable Cooling: Japan's Balanced Approach to Refrigerant Transition, Energy Efficiency, Safety and Affordability



Tetsuji Okada

Past President, Japan Refrigeration and Air Conditioning Industry Association (JRAIA)

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GROWING COOLING DEMAND AND INDUSTRY RESPONSIBILITY

Demand for refrigeration and air conditioning equipment remains strong, in Japan and globally. In Japan, residential air conditioners, commercial air conditioners, heat pump water heaters, chillers, ventilation units, refrigerated display cabinets and condensing units support daily life and business activity. Globally, air conditioner demand continues to grow, particularly in Asia and other warm regions where population growth, urbanization and higher living standards are increasing the need for reliable cooling.

This growth has two meanings. First, cooling is indispensable for modern society. It protects people from heat, keeps food and medicines safe, supports hospitals, schools, offices, shops and factories, and enables resilient urban life. Second, the industry's responsibility is increasing. If growing demand is met by inefficient equipment or high-GWP refrigerants, the sector will become a larger source of greenhouse gas emissions.

The challenge is therefore not to

restrict cooling itself, but to make cooling sustainable. Sustainable cooling requires action on both direct and indirect emissions. Direct emissions come from refrigerant leakage during operation, servicing, repair and disposal. Indirect emissions come mainly from electricity consumption during equipment operation. Depending on the application, climate and electricity mix, indirect emissions can represent a large part of total climate impact. Therefore, refrigerant transition and energy efficiency improvement must be pursued together, as two sides of the same transition.

JAPAN'S POLICY CONTEXT AND THE S+3Es CONCEPT

Japan has committed to carbon neutrality by 2050. Recent national climate and energy policies emphasize steady greenhouse gas reduction, energy conservation, electrification and the use of non-fossil energy. For the refrigeration and air conditioning sector, several policy frameworks are relevant, including the Act on Rational Use and Proper Management of Fluorocarbons, the Ozone Layer Protection Act, the High Pressure Gas Safety Act and the Energy Conservation Act, including the Top Runner Program. Each framework has a different purpose: refrigerant control, ozone layer protection, safety and energy efficiency. However, in actual product development and market implementation, these issues cannot be separated. This is why coordination among policies is important. A measure that is effective from one viewpoint may create difficulties from another viewpoint if the overall balance is not considered. Japan's industry often explains this balance through "S+3Es":

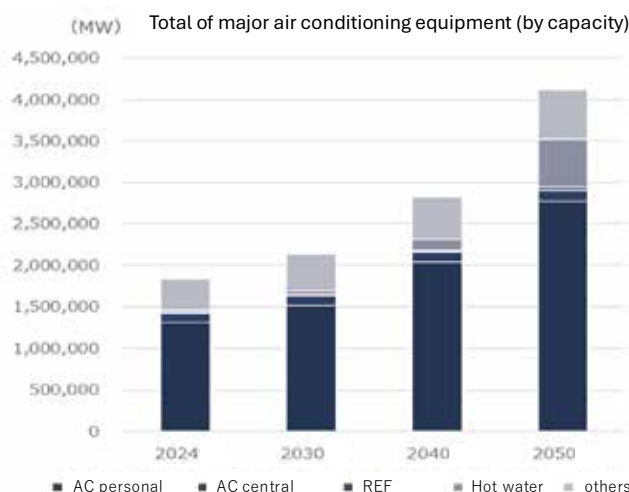


Figure 1-1: Projected global capacity of major RACHP equipment, 2024–2050 (MW).

Safety, Environmental performance, Energy efficiency and Economic feasibility. Safety is non-negotiable, especially when mildly flammable or highly flammable refrigerants are considered. Environmental performance requires zero ozone depletion potential and lower global warming potential. Energy efficiency is essential because much of the lifecycle impact of equipment comes from operation. Economic feasibility is also necessary, because technologies must be accepted by users and spread widely in the market. The S+3Es approach is not an excuse for delaying action. Rather, it is a framework for making climate action durable and scalable. A transition that ignores safety will not be accepted by users, installers or regulators. A transition that ignores efficiency may not reduce total emissions. A transition that ignores cost may not reach households, small shops and ordinary commercial users. All four elements must move together. This point is particularly important for refrigerant selection. The GWP value of a refrigerant is very important, but it cannot be the only criterion. The best option may differ depending on product type, capacity, installation environment, servicing practice, user behavior and local regulation. For example, a refrigerant suitable for factory-built small equipment may not be suitable for large field-installed systems. A practical transition requires careful product-by-product and application-by-application evaluation.

PRACTICAL ACTIONS IN JAPAN

Japan's industry is taking practical actions in several areas. The first is the development and evaluation of next-generation low-GWP refrigerants and compatible equipment. Research and development cover applications such as residential air conditioning, commercial air conditioning and refrigerated display cabinets. The key point is to evaluate not only refrigerant properties, but also equipment efficiency, reliability, safety, manufacturability and actual usability in the market. Refrigerant transition should be treated as a

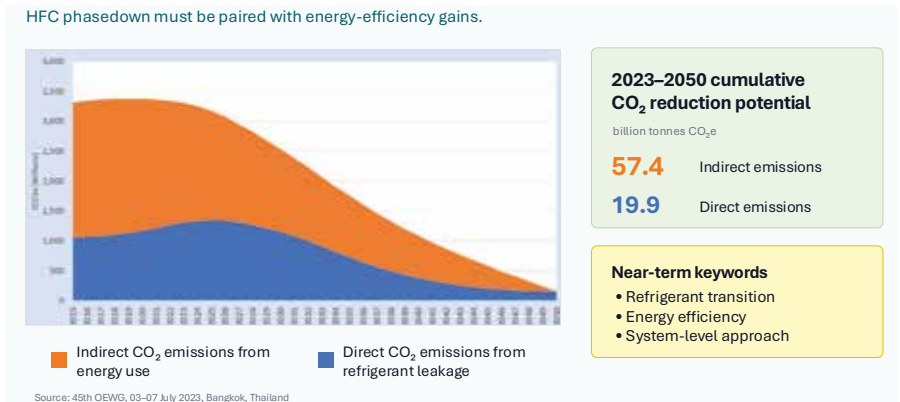


Figure 1-2: Dual trend to reduce Indirect emission and Direct emission.

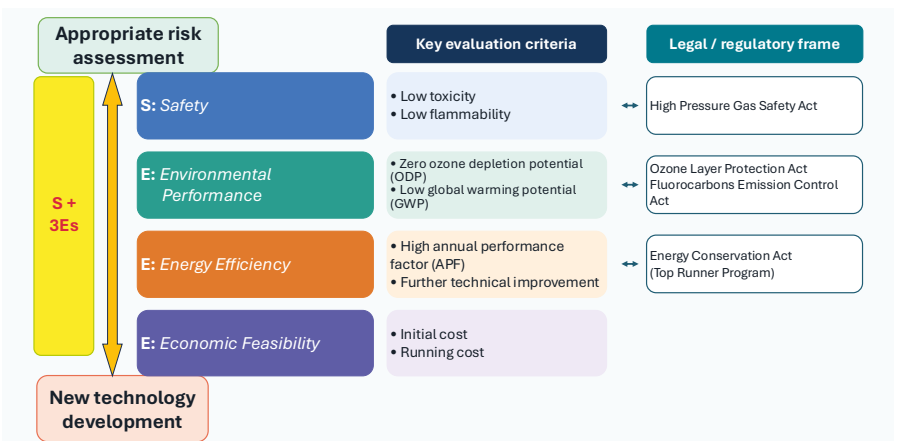


Figure 2: S+3Es framework: Safety, Environmental performance, Energy efficiency and Economic feasibility.

system design issue, not simply as replacement of one working fluid with another. The second area is risk assessment for flammable refrigerants. A3 refrigerants, for example, may have excellent environmental characteristics, but their high flammability requires careful consideration. For chillers and residential air conditioners, risk assessment must cover refrigerant charge, leakage scenarios, ventilation, ignition sources, installation conditions, servicing procedures and end-of-life handling. Safety must be designed into the entire lifecycle of the product. It must also be supported by appropriate standards, training and communication with installers and service technicians. The third area is leakage detection and monitoring. Continuous monitoring systems can help detect refrigerant leakage at an early stage, reduce emissions during use and improve maintenance practices. This kind of measure is sometimes less visible than the introduction of a new refrigerant, but

it is highly practical. It is particularly important for existing equipment already installed in the market. In the future, digital monitoring may also contribute to predictive maintenance, better operation and lower lifecycle cost. The fourth area is refrigerant recovery and reclamation. Even if new equipment shifts to lower-GWP refrigerants, existing equipment still contains a significant amount of HFCs. Proper recovery at servicing and disposal, followed by reclamation and reuse where appropriate, can reduce demand for virgin refrigerants and support a circular economy. Reclamation can serve as an important bridge measure during the transition period. It also sends an important message: refrigerant management does not end when equipment is sold. The responsibility continues throughout the lifecycle. These actions show that refrigerant transition is not only an upstream technology issue. It also involves product design, field installation, servicing, leakage prevention, recovery infrastructure,

recycling and user acceptance. The more ambitious the transition becomes, the more important these practical elements will be.

FROM EQUIPMENT TO SYSTEMS

The next challenge is to move from equipment-level thinking to system-level and lifecycle thinking. Equipment efficiency and refrigerant characteristics remain essential, but carbon neutrality by 2050 requires a broader view. In Japan, whole-life carbon assessment for buildings is becoming an important policy topic. Air conditioning, ventilation, refrigeration and heat pump systems are closely connected with building energy use. High-efficiency equipment and heat pump technologies can contribute greatly to reducing operational emissions. At the same time, embodied carbon, replacement cycles, refrigerant emissions and maintenance practices are becoming part of the wider discussion. The important issue is harmonization. Equipment-level performance indicators, building energy evaluation, refrigerant management and whole-life carbon assessment should not develop independently without coordination. If each system uses different assumptions or incentives, manufacturers, designers, installers and users may face confusion. The goal should be to encourage real CO₂ reduction, not merely compliance with separate indicators. Heat pumps also have an important role. As electricity becomes less carbon-intensive, efficient heat pump technologies can contribute to decarbonization of heating, cooling and hot water supply. Their contribution, however, should be evaluated in the broader context

of system performance, building operation and lifecycle emissions. In this sense, the discussion on sustainable cooling is expanding beyond equipment itself to buildings, energy systems and society as a whole.

INTERNATIONAL COOPERATION

Refrigeration and air conditioning is a global industry. Refrigerants, components, products, standards and regulations move across borders. International cooperation is therefore essential. Japan has participated in international standardization and exchanges with industry associations and stakeholders in Asia, Europe, the United States and other regions. Such cooperation helps improve mutual understanding and supports more practical rule-making. This cooperation is especially important for developing countries and high ambient temperature regions where cooling demand is expected to increase rapidly. These regions have an opportunity to avoid locking in inefficient equipment and high-GWP refrigerants. However, solutions must be practical and suited to local conditions, including climate, building types, electricity systems, safety rules, service infrastructure and economic capacity. Japan's experience may offer one useful lesson: ambition must be combined with implementability. Sustainable cooling requires not only products, but also standards, training, safety rules, recovery infrastructure, maintenance capacity and market support. Simply transferring a technology or regulation from one region to another may not be sufficient. Each country needs a pathway that reflects its own circumstances, while remaining

aligned with global climate goals.

CONCLUSIONS

The refrigeration, air conditioning and heat pump sector is both part of the climate challenge and part of the climate solution. Cooling demand will continue to increase, and access to cooling is essential for health, food security, productivity and resilience. The task is not to reduce the importance of cooling, but to make cooling sustainable. The main message of this article is that sustainable cooling requires balance. Lower-GWP refrigerants are indispensable, but GWP alone cannot determine the best pathway. Energy efficiency is essential, but it must be pursued together with refrigerant management. Safety is non-negotiable, especially when flammable refrigerants are used. Economic feasibility is also necessary, because technologies must spread widely in the real market to deliver environmental benefits. Japan's S+3Es approach provides a practical framework for this transition. Looking toward 2050, the industry must continue to develop low-GWP refrigerants and high-efficiency equipment, improve leakage detection, strengthen recovery and reclamation, assess whole-life carbon and contribute to international cooperation. Ten years after the Kigali Amendment, the global cooling sector should move from commitment to implementation through realistic, safe, affordable and scalable solutions. The challenge is complex, but the direction is clear: cooling must remain available, reliable and useful for society, while becoming compatible with a carbon-neutral future.

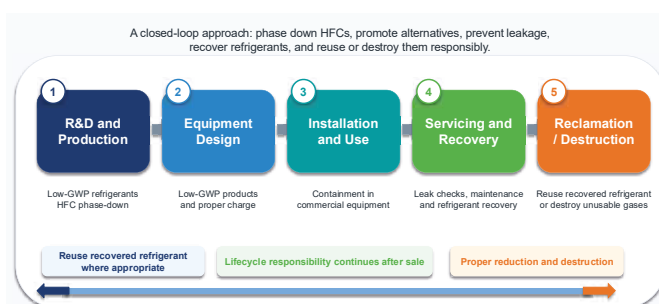


Figure 3: Lifecycle Refrigerant Management

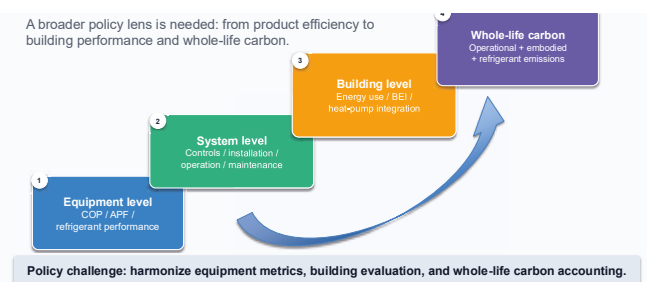


Figure 4: From Equipment Performance to System and Whole-Life Carbon Thinking

The Kigali Climb: Managing Risk in Australia's Ongoing Refrigerant Transition



Mark Vender

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(AIRAH)*



Willow Aliento

Journalist and Editor

A FAST START

Australia moved early to address the climate risks of high-GWP refrigerants. At the Commonwealth government level, the late Patrick McNerney co-chaired the Montreal Protocol negotiations that led to the 2016 Kigali Amendment to phase down HFCs. In 2018, one year ahead of the Kigali Amendment officially coming into force globally, Australia introduced bulk import quotas for HFCs that could be tightened over time to achieve the target of an 85% reduction by 2036, based on average HFC imports and 75% of average HCFC imports for the period of 2011–2013. As Figure 1 shows, Australia's domestic HFC phase-down was also set at 25% lower than the baseline required under the Montreal Protocol. As a result, over the past decade, Australia has consumed smaller volumes of HFCs than Montreal Protocol obligations permit, while still

addressing industry requirements in the refrigeration and air conditioning sector.

"We got off to a really good start," says Peter Brodribb, Managing Director of Expert Group, a consulting firm which has been researching Australia's refrigerant bank and usage for the past two decades.

"Australia decided that we could choose an accelerated phase-down relative to the Kigali Amendment. At the time that made a lot of sense because we had a bit of a head start in 2017." Brodribb notes the HFC phase-down was well supported by established schemes for product stewardship and technician licensing. "One thing that Australia has historically and still continues to do really well, relative to (some) other countries, is we do have a very good refrigerant reclaim program." Refrigerant Reclaim Australia (RRA) operates the nationally authorised product stewardship scheme for refrigerants, through which refrigerants are recovered and destroyed at end of life. It is funded by industry, through levies on imported refrigerant. Each year, about 500 tonnes of refrigerant are destroyed through the RRA scheme. Though there is undoubtedly room for improvement (and the scheme is currently undertaking a review), Brodribb estimates that 2,500 tonnes of refrigerant are retired annually, putting Australia's recovery and destruction rate at about 20%. Chair of the Australian Refrigeration Council, Dr Greg Picker, notes this figure does not include reclamation or recycling which is likely to be (combined) larger than the destruction amount.

"So somewhere around 40 to 50% of refrigerant may be recovered," Dr Picker says. Another positive is Australia's licensing scheme for

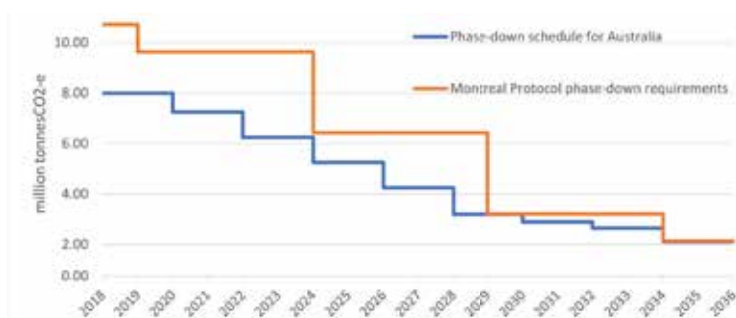


Figure 1: Australia's HFC phase-down schedule against Montreal Protocol phase-down requirements.

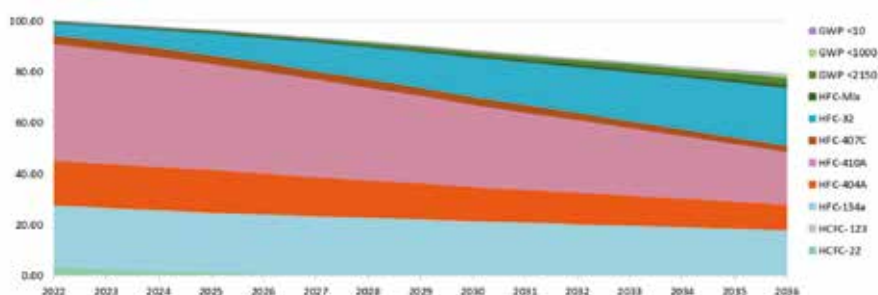


Figure 2: Refrigerant bank by species from 2022 to 2036 in Mt CO₂e.

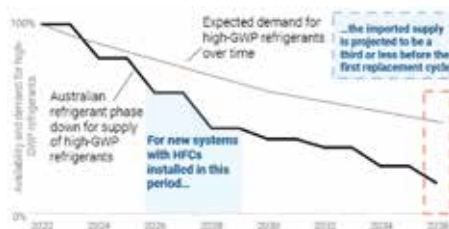


Figure 3: Graph from the Freeze Frame discussion paper showing the looming shortfall in supply.

refrigerants, according to Brodribb. The Australian Refrigeration Council administers the national scheme, issuing licenses for refrigerant handling and trading. This supports responsible management of scheduled substances such as HFCs and HCFCs in Australia's HVAC&R systems. Sami Zheng, CEO of the Australian Institute of Refrigeration Air Conditioning and Heating (AIRAH), says detailed information about Australia's refrigerant bank and usage also helped with the phase-down.

"Thanks to the work of Expert Group on the Cold Hard Facts series of reports, with support from the Commonwealth government, Australia has longitudinal data over the past two decades that can tell us how we are tracking and where issues might arise," she says.

"This is especially important as we enter a more challenging phase of our refrigerant transition."

OBSTACLES EMERGE

When Australia's HFC phase-down was first implemented, it was envisaged that the quota systems would reduce imports of bulk high-GWP HFCs and that this, coupled with the development and adoption of new technologies as part of the refrigerant transition in larger developed economies, would lead to reduced imports of equipment reliant on these refrigerants. But parts of the market did not respond in this way. One of reasons was stockpiling of high-GWP refrigerant.

"Most of the bulk importers brought in two-and-a-half times the typical stock," says Brodribb. Dr Paul Taylor, Director, Atmospheric Chemicals Policy, Department of Climate Change, Energy, and Environment

also pinpoints stockpiling as an issue.

"It ensured a steady supply of these refrigerants and obscured the price signals that the phase-down would otherwise have provided," Dr Taylor says. According to Zheng, market forces and a lack of awareness about the phase-down saw end-users in some sectors opting for the lowest first-cost solution, rather than considering the availability of refrigerant and related costs in the medium and long term. She points to the continued use of R404A in commercial refrigeration applications as a clear example. The Figure 2 from Cold Hard Facts 4 shows the stubborn presence of high-GWP refrigerants such as R404A, R410A and R134a, related to commercial refrigeration, larger and packaged air conditioning systems, and mobile air conditioning respectively. Another factor affecting Australia's HFC phase-down has been the treatment of refrigerants in pre-charged equipment. The HFC phase-down only covers bulk gas in cylinders; it does not cover HFC imported in pre-charged equipment, as under the Montreal Protocol the refrigerant in this equipment is counted in the country where the equipment is charged. According to the latest edition of Cold Hard Facts, approximately 3,712 tonnes of HFCs contained in more than 3.2 million pieces of pre-charged equipment (including 254 tonnes in devices such as aerosols, consumer goods, fire protection and scientific or electrical equipment and switchgear) were imported into Australia in 2022. Meanwhile, 2,913.3 tonnes of HFCs were imported as bulk gas. Based on these figures, 56% of refrigerant is arriving in pre-charged equipment, sitting outside Australia's HFC quota system.

"In some sectors, there has been continued importation of pre-charged equipment containing high GWP refrigerants," says Dr Taylor. "As a result, businesses and consumers have continued to purchase new equipment that uses these gases, locking in ongoing demand and emissions." Zheng points to VRF systems containing R410A (GWP 2,088) and notes that a large

proportion of vehicles imported into Australia still contain R134a (GWP 1,430). Dr Picker observes that Australia imports a significant proportion of pre-charged equipment from countries in Asia that are on a slower phase-down schedule.

"Our mistake was not putting in GWP limits like much of the rest of the developed world did." He acknowledges that at the time, Australia's government and industry stakeholders had good reasons to think this was unnecessary. For example, the experience with CFCs and HCFCs was that transition without regulation can occur. Meanwhile, other forces are driving demand for refrigerant-based heating and cooling equipment. To achieve the Paris commitment of net zero by 2050, there is a major push for switching gas-burning boilers and heating systems to retrofitted electric alternatives across Australia's building stock. Refrigerant-based heat pumps are one of the key enabling technologies.

"Climate change impacts are also escalating, including longer, stronger and more frequent heatwaves," says Zheng. "This is driving increased demand for space cooling in the residential space and in settings including education and recreational facilities." Although a shift has occurred as a result of the HFC phase-down (Cold Hard Facts 4 confirms, for example, the rapid shift from R410A to R32 in the early 2020s in the small split stationary air conditioning segment), Dr Taylor says many are concerned that it has not progressed rapidly enough.

"This risks demand for HFC for servicing and charging newly installed equipment in some sectors outstripping supply, drastically increasing HFC refrigerant prices and associated costs to businesses and consumers," he says. Brodribb agrees that Australia is consuming refrigerant beyond its means, with wide-reaching and serious implications.

"We're in a situation where our capped quota plus some reclamation is not enough to service the bank based on the existing stock of equipment," he says. "I believe that we're going

to run into a really tight situation, to the point where certain sectors are going to miss out. There's potential that some businesses will suffer more pain than others. It will mostly be the small to medium enterprises that won't be ready for this, and that would be a real tragedy."

ADJUSTING OUR APPROACH

A challenge for Australia has been introducing timely restrictions on particular product classes and refrigerants. Although a ban was introduced on certain small air conditioning equipment (charge size of 2.6kg or less) using refrigerant with a GWP over 750, other proposed restrictions on commercial refrigeration equipment have not been implemented. The pressing need for restrictions across a range of products and refrigerants has led the Commonwealth government to consider other approaches.

"The Ozone Protection and Synthetic Greenhouse Gas Management Act 1989 (the OPSGGM Act) is the primary legislative mechanism for regulating substances listed on the Montreal Protocol (including those added by the Kigali Amendment) in Australia," says Dr Taylor.

"However, these refrigerants have also been subject to regulation as industrial chemicals in Australia since 1990. As industrial chemicals, there is an option to set nationally consistent environmental management standards under the Industrial Chemicals Environmental Management Standard (IChEMS)." According to Taylor, setting standards for HFC under the IChEMS has been identified as the best way to deliver the desired set of regulatory changes in a timely manner. Through the IChEMS policy process, measures are assigned for around 1,000 industrial chemicals each year. Conversely, changes to the OPSGGM Act can take many months or years. Measures can also be extended to non-HFC refrigerants. Currently the OPSGGM Act only deals with "scheduled substances" such as HFCs and HCFCs.

"Australia is a small market at the tail end of the world. We cannot drive

change in technology, but we can be early adopters if the policy settings are well tuned," Dr Picker says.

"We need GWP limits on technology to drive change."

RAISING AWARENESS

There is a need to educate stakeholders, particularly those on the demand side. In late 2025, the Green Building Council of Australia and AIRAH released a discussion paper titled Freeze Frame: Refrigerants as long-term building infrastructure. The project team spoke to building owners, design teams, HVAC and refrigeration professionals and suppliers to ask how ready they are for a future shaped by refrigerant transition. The paper notes that many consumers have low awareness of the consequences of the HFC phase-down, what it could mean for the ongoing service of existing installations and how they could avoid risks of continuing to install HFC equipment. As a result of the discussion paper, work is now commencing on more detailed practical guides for equipment selection. Another barrier that has been identified is a workforce unfamiliar with new technologies.

"Understanding the need to transition is only one part of the equation," says Dr Taylor. "Transitioning away from HFC refrigerants also requires confidence in alternatives. Here, training plays a similar critical role in facilitating uptake of alternatives to HFC refrigerants. It is crucial that the workforce installing and maintaining equipment using new technologies or retrofitting existing equipment (where supported by manufacturers and refrigeration engineers) has the skills and capability to undertake this work." The Australian Government has supported updates to relevant nationally recognised training packages to ensure newly qualified technicians have received appropriate training. Zheng says industry has a key role to play in education and training the workforce. She points to the recent release of an updated Flammable Refrigerant Safety Guide, which aims to improve awareness of how to best manage

the health and safety risks associated with the use and management of flammable refrigerants in stationary refrigeration and air conditioning equipment. The project brought together various industry groups to deliver free resources for the workforce. Other important initiatives are in train. Expert Group has been commissioned to do a rigorous assessment of when the big shortages may occur, with a report expected in the coming months. The Commonwealth government is also focusing more on refrigerants in its Net Zero – Built Environment Sector Plan and Trajectory for Low Energy Buildings.

"For many applications, newer technologies using alternative refrigerants have become mainstream and cost competitive. Investments in new equipment can be coupled with energy efficiency and/or electrification initiatives, with various grants currently available to businesses and consumers across Australia," Dr Taylor says. As we enter the next crucial phase of the HFC phase-down and the broader refrigerant transition, it is important to recognise both the achievements and the challenges ahead. The experiences in individual countries can be instructive.

"The hard problem is inertia," Dr Picker says.

"This is all achievable. Industry needs to recognise the issues, and government needs to support with regulation. We know we can do this – we have done this before and there are enough sensible international examples."

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Sustainable Cooling for Small Island Developing States: Seawater Air Conditioning as a Not-in-Kind Technology



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INTRODUCTION

Cooling is a major energy and climate challenge for small island developing states (SIDS). Rising temperatures, tourism growth, urbanization, and increasing demand for thermal comfort are driving rapid growth in air-conditioning demand. In most SIDS, cooling depends on conventional, energy-intensive vapor-compression systems using electricity generated by imported fossil fuels subject to high prices and volatility and resulting in high emissions. Seawater Air Conditioning (SWAC) is a promising not-in-kind cooling solution that offers lower costs, high reliability, energy reduction up to 90% and near elimination of refrigerant use.

HOW SWAC WORKS

SWAC systems draw cold seawater from ocean depths of 600 – 900 m where water temperatures are low and stable to shore via offshore high-density polyethylene (HDPE) pipes where it is passed through onshore titanium counter-flow heat exchangers to cool separate

closed-loop freshwater systems. This chilled freshwater is then distributed to buildings through either a district cooling network or directly to individual customers. The seawater and freshwater circuits remain separated by the heat exchanger to prevent mixing of the fluids. All materials exposed to seawater (e.g., HDPE and titanium) are selected for seawater corrosion resistance.

The only energy consumption of a SWAC system are standard seawater pumps to overcome drag through the pipelines and heat exchanger. In most conditions, SWAC saves up to 80-90% of the energy used by conventional air conditioning systems.

WHY SWAC MATTERS FOR SIDS

SIDS face high and growing cooling needs, high electricity tariffs, limited electricity generation capacity, and heavy dependence on imported fuel. Tourism sector is the cornerstone for sustainable economic growth of most SIDS and cooling often accounts for more than 50% of electricity consumption at tropical hotels. This

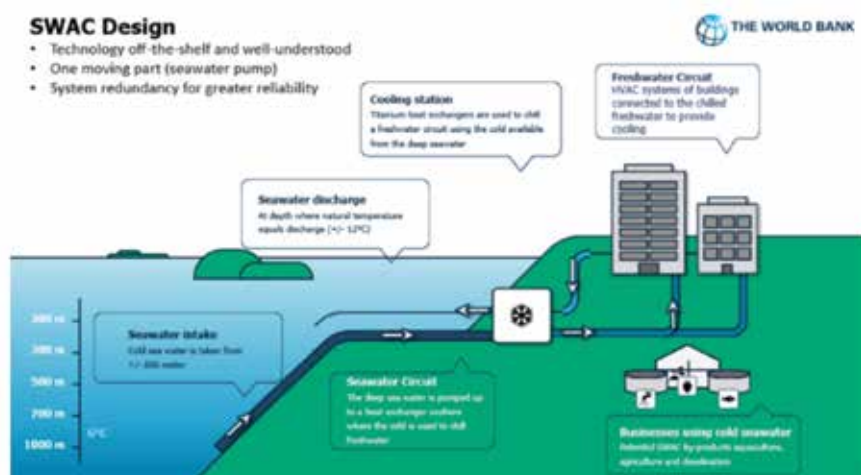


Figure 1: Design of Seawater Air-Conditioning System.



Figure 2: Deployment of SWAC Systems.

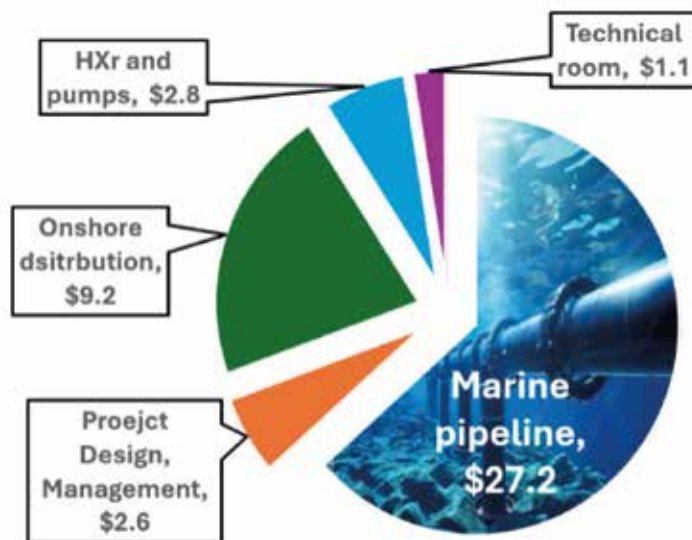


Figure 3: Estimated Capital Expenditure of Grenada SWAC System (in million USD).

cost would be significantly lowered by using a locally available natural cooling resource rather than imported fuels and refrigerants. SWAC supports both climate change mitigation and adaptation anchored around the objectives of the Montreal Protocol and the Kigali Amendment and often comes with co-benefits in the blue economy realm. It can also complement SIDS' clean energy transition, together with renewable energy deployment thereby easing pressure on island power grids. In SIDS, SWAC can form part of a wider

sustainable cooling action plans that include energy efficient ACs, passive building design, district cooling, renewable energy, and climate-resilient infrastructure.

SWAC DEPLOYMENT TO DATE

While not yet widespread in use, SWAC – and variants using cold lake water – have been deployed and used around the world for many years as shown in Figure 2. The track record of these systems is reliability, low costs and high

sustainability, all of which are particularly relevant for SIDS.

IMPLEMENTATION METHODOLOGY AND SITE SELECTION

SWAC projects can be developed through a staged methodology, involving multiple stakeholders in both the public and private domain.

- 1) Screening locations for accessible cold deep seawater that is not too far from the shore to the target intake depth.
- 2) Screening for cooling demand. SWAC works best where cooling load is sufficiently large and dense to justify the cost of the marine pipeline.
- 3) Technical and financial assessments, examining pipeline length and cost of deployment, pumping energy, heat exchanger design, discharge location, and integration into customers' current systems. This also includes financial analysis to assess SWAC cost versus status quo and competing cooling options.
- 4) Environmental and social assessment. The two primary environmental risks are: (i) disturbance of seabed habitats during pipeline installation, and (ii) localized effects from discharge of the warmed seawater.

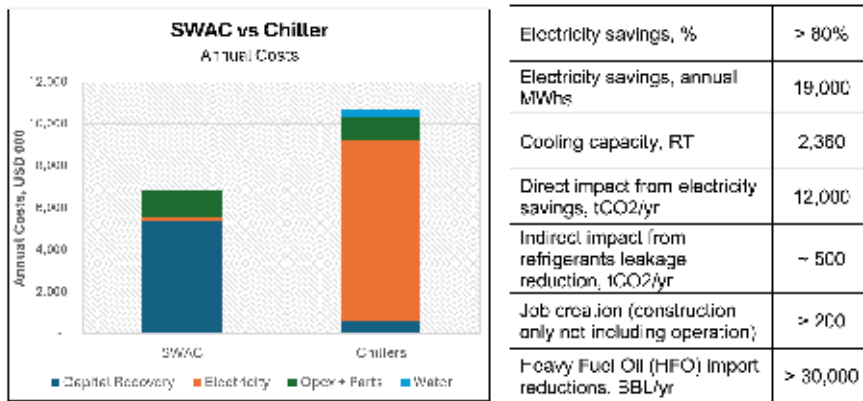


Figure 4: Benefits of Grenada SWAC over Conventional Chillers.

Existing SWAC facilities show these risks can be managed but must be assessed for each SWAC project based on local conditions.

CARIBBEAN EXPERIENCE AND GRENADA SWAC CASE STUDY

This cooling challenge is particularly acute across Caribbean SIDS, where heat stress is intensifying, and where cooling is a frontline climate adaptation need.

Their heavy dependence on imported fossil fuels along with inefficient cooling compounds their fiscal vulnerability in addition to generating emissions. Recent work in the region illustrates the potential for SWAC to be a sustainable cooling solution. Studies supported by the World Bank identified Jamaica, Grenada, the Dominican Republic and Dominica as the most promising SWAC sites in the Caribbean. Subsequent pre-feasibility studies found most of those sites feasible and attractive for SWAC. Grenada is emerging as one of the most advanced SWAC opportunities in the Caribbean.

The proposed system, being developed with World Bank support, would initially supply 2,360 refrigeration tonnes (RT) cooling to four anchor customers: the Maurice Bishop International Airport (MBIA), St George's University, and two private coastal resorts.

The project, with an estimated capital expenditure of \$43.1 million (Figure 3), would be structured as a public-private partnership (PPP) blending lower-cost public funding with commercial investment,

with practically no initial capital investment by end-user, customers and beneficiaries of the cooling service.

Despite the higher capital costs of the SWAC system, the reduction in electricity use of 86% - combined with the relatively high cost of electricity in Grenada - means that the all-in cost of the SWAC system would be up to 30% less than that of conventional air-conditioning serving the same cooling needs. In addition, SWAC would provide numerous other environmental, economic and other broader co-benefits in the blue economy domain.

Figure 4 compares the annual costs and benefits of Grenada SWAC system against conventional chillers with the same cooling capacity.

MAURITIUS SWAC PROJECT

The World Bank Group is also supporting development of a SWAC project in Mauritius in the Indian Ocean to serve major hotels on the coast.

To date, two major hotels have signed letters of intent (LOIs) to pursue SWAC and others are currently negotiating their one LOIs. The first two sites would encompass 6,500 refrigeration tonnes (RT) and have a capital cost of approximately EUR 83 million.

GOING FORWARD

SWAC has the potential to lower costs for cooling while also greatly lowering energy use and direct and indirect emissions.

This is particularly valuable in island power systems where electricity is expensive, and its supply is often constrained.

SWAC also has refrigerant-related benefits because it replaces conventional chillers and their use of high-GWP refrigerants.

SWAC improves competitiveness for end-users, eliminates noise and heat rejection from conventional cooling and supports broader blue economy strategies by using the cold, deep seawater for aquaculture, desalination and marine research.

However, SWAC also faces barriers to wider deployment, including high upfront costs for offshore and onshore infrastructure.

Its viability is highly site-specific, depending on access to deep cold water nearby and sufficient cooling demand. It also requires specialized engineering and maintenance capacity, which may need to be brought in for some locations.

While SWAC is not a substitute for all other cooling measures, where conditions are favorable, it can become a cornerstone of a sustainable cooling strategy for SIDS. Combined with energy efficiency, passive design, renewable power, resilient infrastructure, and strong marine stewardship, SWAC can help islands in their path towards clean energy transition while meeting the rising cooling needs without deepening their dependence on high-carbon and high-GWP refrigerant based cooling pathways.

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COOLING ACTION PLANS, CLIMATE CHANGE DEVELOPMENT REPORTS AND THE EVOLUTION OF THE POLICY LANDSCAPE



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This contribution provides selected insights on how policy planning established itself through Climate Change Development Reports (CCDRs) and National Cooling Action Plans (NCAPs) and remains relevant today, in the spirit of the Kigali anniversary and of this International Special Issue.

I focus on selected achievements and hurdles, and on how they were overcome. I start with the beginning: NCAPs were developed under the Montreal Protocol's Kigali Amendment and the Paris Agreement and established a policy framework to guide regulatory measures, incentives, and investment strategies. CCDRs were proposed and developed at the World Bank in 2019, to look at the national growth strategies and simulate carbon taxes, subsidy removals, climate impact on fiscal stability and GDP. As potential twins, NCAPs provide targeted roadmaps and CCDRs evaluate broader economic, physical, and climate-related risks.

At the present, a few policy successes and hurdles can be singled out. The first accomplishment is their validation, as CCDRs have become a permanent core diagnostic tool. Despite increased policy uncertainties, their rollout is being expanded. Correspondingly, driven by the Global Cooling Pledge and

frameworks like the UNEP Cool Coalition, NCAPs have become established policy documents focused on integrating passive cooling, appliance efficiency, and HFC phase-downs into updated national climate commitments (NDCs 3.0). It should be noted that criticisms were raised, at inception and during the formation of the tools. For example, CCDRs were insufficient in advising and supporting the private sector, they lacked of realistic proposals for financing needed investments and gave insufficient attention to public sectors indebtedness, domestic capital and financial markets, the limitations of green finance instruments. Similarly, NCAPs were criticized for neglecting enforcement or aspects of supply chain and workforce gaps. Yet, policy planning outlived criticisms and severe obstacles. In the case of CCDRs, obstacles ranged from political gridlock to funding cuts, from public resistance or backlash to energy shocks and COVID-19. The pandemic itself spurred a global recession with massive poverty inversion in Africa, severe budget diversions and climate de-prioritization. For refrigeration and sustainable cooling, the pandemic reshaped policy, temporarily stalling climate diplomacy (e.g. COP26 and NDC reporting) and integrated climate goals into pandemic economic bailouts (e.g. the EU pioneered this approach with the NextGenerationEU). At the time when CCDRs were being rolled out, massive public debt accumulated by African governments to manage the COVID recession left a lasting hangover on climate plans, creating an architectural disconnect policy planning. The resulting debt servicing costs crowded out the capital needed to invest in climate adaptation, including refrigeration and cooling, as I saw first-hand, for example, in the case of Somalia.

Policy planning outlived criticisms and severe obstacles through flexible design, coalition-building, and strategic adaptation; NCAPs and CCDRs have become a permanent core diagnostic tools that help measure drops in emissions and incentivize energy-efficient cooling systems. For example, the Vietnam CCDR explicitly demanded strict energy efficiency

standards tailored directly to cooling devices and consumer appliances. Several CCDRs emphasized policy reforms towards space cooling and natural ventilation. The Brazil CCDR integrated cooling directly into its economic and labor assessments, linking temperature deviations directly to immediate drops in industrial and economic output, showing the absolute necessity of scaling up clean and highly efficient cooling technologies to buffer the private sector against a 2% to 3% drop in localized capacity utilization during extreme heat period. Yet, more needs to be done particularly for the private sector in emerging markets—where recent data continue to reveal that few firms are taking measures to adapt. Finally, at the frontline of the policy agenda on jobs, many CCDRs discuss the importance of active labor market policies in facilitating the job transitions in the face of shifting demand.

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Every year on 26 June, we celebrate the World Refrigeration Day, highlighting the vital role of refrigeration in our daily lives. Pictured here at the Politecnico di Torino.

A Scalable Deployment Model for Sustainable Cooling Under the Kigali Amendment: the ACES Hub and SPOKE Approach



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INTRODUCTION

The Africa Centre of Excellence for Sustainable Cooling and Cold-chain (ACES) was conceived in 2020 as the flagship workstream under the Sustainable Cooling and Cold-Chains (SCCCS) Programme, built and co-created through a collaborative partnership between UNEP, the Governments of the UK and Rwanda and a consortium of UK Universities led by the University of Birmingham. Supported with UK Defra funding of over \$35m, and with further support from the Government of Rwanda, grants and cold chain industry, the SCCCPS Programme aim has been to increase and accelerate the adoption of resilient, efficient, inclusive and climate-friendly cooling and cold-chain. A core focus of activities has been to facilitate and enable an optimised implementation of the Kigali Amendment to the UN Montreal Protocol, providing valuable support to developing countries for technical capacity and insights on global best practice to rapidly decrease or avoid HFC use as they transition from ozone depleting substances in cooling and cold chains.

The work since 2020 has built the tools to support the foundational and readiness levels in countries that enable leapfrogging to more sustainable cooling and cold-chain infrastructure and the conditions to bring to market accessible and

available climate-friendly, energy efficient cooling solutions, accelerating the transition in Africa and other developing markets to sustainable refrigeration reducing food loss and improving vaccine supply chains. The role of these specialised CoE is to support the development of policies and tools and offer technical assistance through undertaking and sharing research, demonstrations and knowledge transfer to rural communities through:

- Upgrading training content and infrastructure that can be coordinated through specialised Centre of Excellence (CoE) (including through a cross-sharing network of physical and thematic CoE and through their SPOKES).
- Driving technology change through in-market testing and demonstration.
- Technical support for adopting energy efficient technologies including product design, manufacturing and assembly.
- Developing the local skills and training so that equipment is specifically designed for the local markets and can be installed operated and maintained by local people to a high standard. For ACES, this means “developed and tested in Africa for Africa” through the state-of-the-art Environmental Test Chamber which has been built.
- Assessing and designing national systems to meet strategically

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Figure 1: The equipments loaned at the Lari Horticulture Co-operative Ltd.

important national and international priorities and objectives.

These reference materials have been built out of years of detailed needs assessments, dedicated research, development of bespoke training programmes and business models and other products that can now support adoption through CoE and a hub and SPOKES model deployed through a hybrid online and physical approach. At ACES, this “hub and SPOKE” model represents an Africa-centric programme which is “Born in Rwanda, pan-Africa and global in vision” with the ACES “Hub” acting as the African research, testing and knowledge development Centre which then interacts through country-led “SPOKES” (Specialised Outreach and Knowledge Establishments) which are developed to share and implement the research, innovation and knowledge in different African countries, test validate and localise the approaches in actual market conditions and build capacity in countries.

Progress to Date – Moving ACES to become a Centre of Reference and Blueprint for others

The SCCCS Programme has been developed through two main phases. The first has been the design and development stage to deliver foundational build support that has led to the first physical specialised CoE in Rwanda – ACES. Through the CoE activities under the SCCCS Programme, the reference materials, blueprints and process maps have all been developed and are now ready for refining, deploying and testing in other markets, setting the stage for the next phase of the Programme through enhanced implementation and deployment. A core component in this next phase is to validate how these materials can be made available, used and deployed through specialised CoE and SPOKES to deliver sustained operations. Through further Defra funding provided in mid-2025, work has focussed on actively developing an environment for stakeholder collaboration to explore enhanced opportunities for co-financing, cost-recovery and partnerships to help the Programme

and activities at ACES to become self-sustaining. This additional funding continues to provide transitional support as the programme moves from demonstration to proof-of-concept stage and to provide more confidence for third-party donors to fund expansion of ACES and its SPOKE network. During this period, the focus is on how to ensure ACES can move from being a specialised CoE to become a Centre of Reference which others can learn from, and which can be adapted to meet local needs and circumstances. Defra support during this period will therefore help to ensure the development of a sound operational business model with a co-financing plan for ongoing sustained operations, based on its technical and policy assistance and services. These can continue to position ACES as a knowledge and innovation centre, providing a global collaborative platform for networking with industry and service providers for better outreach on technologies and ensuring continued support for training and technical support to technicians and to local stakeholders on technical and policy issues including product design and local adaptation of technologies and approaches in a cost-effective manner.

Implementation through the ACES Reference SPOKE in Kenya

Through its “Hub and SPOKE” approach, SPOKE activities are now being scaled supporting operations in Kenya, which serves as the reference SPOKE, and evolving and validating the approach which can then be rolled out for different African countries to deploy the solutions tailored for local markets and communities. Through a close relationship between the hub in Kigali and activities for the first SPOKE communities in Kenya, the knowledge, training and support is now being disseminated to deliver local/near to market training and community support and put into practice and demonstrate real world solutions. The establishment of SPOKES is an integral part of meeting the ambition of the SCCCS Programme objectives as SPOKES are the extended vehicle to enable dissemination of the knowledge and

tools developed. The African Centre for Technology Studies (ACTS) as the lead in-country delivery partner in Kenya, supported by the ACES hub and the wider SCCCS Programme partners, has been developing the delivery and implementation of the reference SPOKE. Since March 2025, the tools developed under the SCCCS Programme are now being refined, deployed and tested through the first SPOKE Community in Kenya, and the establishment of a new farmer co-operative (Lari Horticulture Co-operative Ltd.) as the pilot community. A key activity is to develop new financeable community-based business models and approaches for testing cold-chain integration in actual market conditions and assess how value is brought back to the community and to the smallholder farmers. This enables farmers and cooperatives to build financeable and investment-ready proposals to invest in their own fit-for-purpose cold-chain infrastructure.

The SPOKE Reference Approach

Activities are delivered through two phases:

- Phase 1 – Engagement, selection and business model development
- Phase 2 – Business model with technology integration testing and validation

Phase 1 through a series of diagnostic and desk-based assessments led by ACTS and supported where needed by the ACES Hub expertise, candidate communities are selected through a detailed mapping process which considers the existing co-operatives, farmer groups, SMEs and other actors in the chain, the markets and value-chain opportunities and community technical and infrastructure readiness levels. Through an EOI process, community groups are then shortlisted and invited to a series of introductory sessions and training activities. These engagements provide an opportunity to further explore their cold-chain needs and opportunities, while fostering a more detailed dialogue on their current business models and the potential benefits of integrating cooling solutions and cold-chain systems to assess community readiness. Most ready communities

are then selected from the wider group to move through to the next stage where the SPOKE in-country team deliver the support, governance and operational systems and targeted training necessary to support community leaders and the wider community establish a grassroots, community cold-chain ecosystem and refine their business models ready for testing. Ongoing engagement and support continue to be provided to the wider group linked to training and capacity building programmes and these communities can re-engage at future calls. **Phase 2** then enables one selected community to fully test and validate their developed business model through a basic package of cold-chain equipment which is loaned and deployed to the community free of charge for a set period. This includes pre-cooling, cold storage, processing equipment, integrated with telemetrics and ongoing mentoring and support across this period to refine, test and evaluate performance and impacts in their own communities and connect to new markets before making a decision to purchase their own cold-chain equipment and finalise their validated investment ready business cases. Enabling such testing and validation prior to investment removes the upfront risk for communities and also builds confidence amongst investors and financial institutions to provide financing given the availability and evidence of economic viability and return on investment. Furthermore, communities who are able to benefit from such a proof of concept approach can then act as “model communities” and themselves become demonstration and learning sites, providing the evidence and knowledge to other communities underpinned by the SPOKE teams as a local facilitator.

The approach and results from the Lari Horticulture Co-operative Ltd pilot

The Lari Horticulture Co-operative Ltd recently celebrated a key milestone a year after being established. Over 200 smallholder farmers are already registered and many are already earning over 50% higher returns on their produce, thanks to improved

quality, extended shelf life, and access to premium markets. The loaned equipment at Lari has enabled trial and testing of a cold-chain that extends from the field to the marketplace. In the field, the first step towards the market is a quality control stage and at this point, the farmer is provided with a “goods-received form” for the accepted produce. Based on this paperwork, the farmer will be paid within a maximum of a week and orders by end markets are fulfilled by the cooperative’s sorter staff through the use of a single cabin pickup truck. The vehicle has a 20mm sandwich panel insulated body to prevent temperature related spoilage of the produce during transit. Fast-spoiling products, such as herbs, are immediately packed into cooler boxes with Phase Change Material (PCM) packs to reduce their stored temperature during transit. Less sensitive products are simply stacked in ventilated crates for the journey.

The crops are taken to the aggregation facility, where they are graded according to the specific buyer’s specifications. A pre-cooling unit, which is integrated into the 5-tonne solar-powered cold room removes field heat from the fresh produce. The aggregated and graded produce is then transported from the aggregation centre to wholesale or retail buyers using a 5-tonne refrigerated truck. Both the truck and the cold room contain their own remote monitoring system, which enables traceability of temperature control throughout the journey, thereby ensuring the integrity of the cold-chain from farm to market. Integrity of the cold-chain is essential to maintain the quality and freshness of the produce all the way to the market, without it the value-add of cooling is lost. The Lari pilot as part of the wider Kenya SPOKE activities therefore trains all stakeholders in best practice and best handling of produce, enabling the highest standards to be achieved and guaranteed for the end markets.

Learning from Lari and refining the approach

A comprehensive technical review of the Lari Cooperative pilot has been conducted, assessing facility uptime, energy consumption, utilization, operational efficiency, maintenance,

and business performance. Building on these lessons, a Technical and Infrastructure Readiness Assessment Framework has been developed and is now being integrated into the next community due diligence processes currently being assessed and implemented. Other elements of the Kenya SPOKE programme have also been refined to reflect the operational experience, emerging diagnostic evidence and lessons from the Lari Cooperative and which are now being further contextualized and applied to Kenya’s horticultural systems, county-level implementation realities and smallholder aggregation challenges. These specific lessons from the Lari pilot are informing the minimum institutional, technical, operational, and financial requirements needed to establish commercially viable, investment-ready, and scalable Community cooling and cold-chain approaches. Building on the work to date at the Lari Cooperative, a second community engagement programme working with Ustawi Afrika, a social enterprise, was recently launched within the Kenya reference SPOKE.

Scaling the Kenya SPOKE model

Earmarked funding from a new partner has been secured to support the SCCCS Programme in Kenya over the next three years, complementing the existing and ongoing Defra support at the wider SCCCS Programme level and aimed at supporting the SPOKE activities in Kenya. Funding will support delivery and impact through validation and scaling of the SPOKE and community engagement model through replication. The project will secure impact through scaling up outreach to more smallholder farmers in Kenya, aiming to expand to three new SPOKE regions in Kenya and increase the numbers of smallholder farmers and communities that can develop, test and validate their inclusive business models through project support, and prepare for sustainable cold chain investment enhancing the ambition level that has currently been delivered through Defra funding and building on the lessons to date and refinement of the overall replicability and scaling of the approach.

10 Years After Kigali Amendment on Montreal Protocol: The Carts Before the Horses in AFRICA!



Madi Sakandé

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THE AFRICAN CONTEXT: WHEN THE FOUNDATIONS OF THE TRANSITION ARE STILL BEING BUILT

Ten years after the adoption of the Kigali Amendment, the global refrigeration and air-conditioning (RAC) sector is entering a decisive phase. The transition towards lower-GWP refrigerants is progressing, and countries are increasingly developing policies and programmes aimed at reducing HFC consumption. In Africa, however, the implementation of these commitments needs to be considered within a particularly complex and uneven regional context. While a number of countries have made significant progress in establishing regulatory frameworks, strengthening national institutions and preparing their Kigali Implementation Plans (KIPs), important gaps remain at the level of the RAC sector.

The main challenges in the region include limited technical capacity, the prevalence of informal technicians, and especially the growing risks associated with the handling of flammable alternatives. Strengthening technicians' theoretical and practical skills is indeed essential to ensure that alternative refrigerants can be introduced safely and effectively. This is particularly relevant as many of the alternatives promoted under the Kigali Amendment have different safety characteristics from the refrigerants traditionally used in the sector, including flammability, toxicity or higher operating pressures.

In several African countries, therefore, the challenge is not simply to replace one refrigerant with another, but to build the foundations that make such a transition possible. These foundations include

competent technicians, accessible practical training, appropriate tools and equipment, effective certification or competency-assessment systems, adequate safety standards, functioning refrigerant recovery and management practices, and effective cooperation between policy makers, and technicians.

These challenges should not be interpreted as evidence that Africa is unable to implement the Kigali Amendment. On the contrary, they highlight the need for a transition strategy that reflects the realities of the region. Africa faces rapidly increasing demand for cooling, while large parts of its population still lack reliable access to adequate and affordable cooling services. At the same time, the continent is expected to experience some of the fastest growth in the cooling market in the coming decades.

The transition therefore represents not only an environmental obligation, but also an opportunity to establish a safer, more professional and more sustainable cooling sector. The central question is consequently one of sequencing. Can the sector be expected to move rapidly towards increasingly sophisticated refrigerant transitions when the basic technical, safety, market-control and enforcement conditions required to support that transition are not yet consistently in place? In this sense, the African experience suggests that the "horses" of policy ambition and technological transition cannot be placed before the "cart" of the basic capacities needed to implement them. Training technicians, establishing competency and certification systems, improving refrigerant identification and trade controls, strengthening customs cooperation, formalising good servicing practices and ensuring

that equipment and refrigerants are appropriately labelled are not secondary measures.

They are the foundations upon which the safe and effective implementation of the Kigali Amendment must be built. The carts are being put before the horses in some African countries. Several equipment operating with flammable refrigerants is already on some markets in Africa, knowing that any uncontrolled handling would cause a hidden fire. To prevent the RAC sector, so essential for the development of Africa and its food sovereignty, from inflaming both technicians and users, a vast awareness campaign and training program must be undertaken beforehand.

Across the continent, the risk of explosions is amplified by the fact that many technicians are poorly educated, so training sessions have been provided sparingly to only a few refrigeration engineers and government personnel in some countries. This is an insufficient action, given that the handling is done by more than 85% of technicians who have not yet been trained. This is therefore the place to solemnly launch an appeal, by professionals, worthy of the name and who measure the extent of the danger, to take energetic measures without delay, in terms of training and awareness. The following recommendations are addressed to specific stakeholders.

The recommendations are designed to be actionable and realistic within the African context, considering the informal sector dynamics and resource constraints.

Recommendations for Governments and policymakers

Governments of African countries should update national safety regulations to explicitly address flammable refrigerants. These regulations should adopt international standards such as ISO 5149 and ISO 817 as national requirements, establish maximum charge limits for different occupancy types, and mandate the use of flammable rated tools and equipment. Governments should introduce mandatory technician certification for anyone handling flammable refrigerants. Certification should require demonstrated competence in safe handling procedures, leak detection, recovery, and emergency response. Certification should be renewable through periodic refresher training. Governments should establish formal incident reporting systems for refrigerant related accidents. Reporting should be mandatory for all incidents resulting in injury, fatality, or significant property damage. A central database should be maintained to track incidents, identify trends, and inform policy. Governments should strengthen market surveillance to prevent the sale of mislabelled

or counterfeit refrigerants. Import controls should be enforced to ensure that all refrigerant cylinders are properly labelled with the refrigerant type, safety classification, and hazard warnings in local languages. Government should cancel or reduce the taxation on the importation of refrigeration equipment and tools and provide incentives to RAC sector to be able to buy the right tools and equipment for best

Governments should enforce work permit and risk assessment requirements for refrigeration and air conditioning work involving flammable refrigerants. Work permits should specify the safety measures to be followed, the tools to be used, and the personal protective equipment required.

Recommendations for Training Institutions and Educators

Technical and vocational education and training (TVET) institutions should integrate comprehensive modules on flammable refrigerant safety into their curricula. These modules should cover refrigerant properties, flammability characteristics, ignition sources, safe handling procedures, leak detection, recovery, and emergency response. Training should be practical and hands on, not merely theoretical. Trainees should practice using flammable rated leak detectors, explosion proof recovery machines, and personal protective equipment. Simulated leak and fire scenarios should be included to build muscle memory and confidence. Training providers should develop accessible, affordable, and convenient training options for informal sector technicians.

Mobile training units, evening classes, weekend workshops, and peer to peer learning should be explored. Training materials should be available in local languages and should use visual and practical methods appropriate for learners with limited literacy. Training should include modules on behavioural change, not only technical skills. Trainees should understand the importance of work permits, risk assessment, logbooks, and



The first training mission carried out within the project "Rwanda – Strengthen Capacity for Sustainable Cooling and Refrigeration" has been successfully completed in Rwanda, marking an important step in the development of technical skills for the refrigeration and air conditioning sector, with a focus on safety, energy efficiency and the transition towards lower-climate-impact cooling solutions.

compliance with safety procedures. The Theory of Planned Behaviour and Diffusion of Innovations frameworks suggest that training should also address social norms and perceived behavioural control.

Recommendations for Industry Associations

National refrigeration associations should expand their reach to informal sector technicians. Associations should offer low cost or free training, tool libraries, and certification pathways. They should also serve as reporting bodies for incidents, documenting accidents and sharing lessons learned with members. Associations should advocate for regulatory reform and enforcement. They should engage with governments to develop safety regulations, certification schemes, and incident reporting systems. They should also work with importers and distributors to ensure that only properly labelled, safety rated refrigerants and cylinders enter the market. Associations should promote a safety culture among their members. This includes regular safety bulletins, case studies of incidents, recognition of safe practices, and peer accountability mechanisms.

Recommendations for International Partners and Agencies

International organizations such as UN Agencies (UNIDO, UNEP, UNDP and World Bank) and some national cooperation Agencies (JIRCA, GIZ,...) should ensure that projects supporting the Kigali Amendment include dedicated components on workforce safety. Funding should be allocated for training, tool provision, regulatory development, incident reporting systems and support the national RAC associations. Partners should support the establishment of regional centres of excellence for flammable refrigerant safety.

These centres could develop standardized curricula, train trainers, conduct research, and provide technical assistance to governments and associations. Partners should finance the development and

distribution of affordable flammable rated tools for informal sector technicians. Subsidies, tool libraries, or financing mechanisms could be piloted and scaled. Partners should support the creation of continental incident reporting networks. A shared database of refrigerant related accidents could be hosted by U-3ARC, allowing countries to learn from each other's experiences.

Recommendations for Technicians and the Private Sector

Technicians should actively seek out training on alternatives (flammable, toxicity and high pressure related) refrigerants, even if not required by law. They should read labels on refrigerant cylinders, follow safety procedures, use appropriate tools, and never take risks with open flames or ignition sources in the presence of leaked refrigerant. Workshop owners and employers should provide personal protective equipment, flammable rated tools, and safety data sheets for all refrigerants used. They should enforce work permit and risk assessment procedures and should not allow untrained technicians to handle flammable refrigerants. Refrigerant distributors should ensure that all cylinders are properly labelled with the refrigerant

type, safety classification, and hazard warnings in local languages. They should refuse to sell refrigerants to uncertified technicians and should provide safety data sheets with every sale. Equipment manufacturers should design systems with clear labelling indicating the refrigerant type and safety requirements. They should also provide training materials and safety instructions that are accessible to technicians with varying literacy levels. While RACHP industry can be a source of pollution in A2 countries,

The lack of reliable RAC industry is the major issue for the climate in A5 countries because of the CO₂ emissions from post-harvest losses due to lack of cold chain.

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The advanced programme is designed for trainers and will also include a component of the SKILLSAFE EU project, focusing on the installations of systems containing the flammable refrigerant R290 (propane).

How Much Does Your AC Really Warm the World? An Evaluation Using Life Cycle Temperature Response



^a Baolong Wang



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COMFORT DILEMMA

Heatwaves that once made headlines are becoming a regular feature of summer in many parts of the world. In the Northern Hemisphere, demand for air conditioning (AC) is spreading northward while continuing to grow in the south.

For older people, patients and others exposed to dangerously hot conditions, cooling is not simply a luxury. Yet air conditioners consume electricity and use refrigerants that may be potent greenhouse gases, so cooling is often presented as a technology that worsens the problem it is meant to solve. With global space-cooling demand projected to grow strongly, this concern deserves measurement rather than rhetoric. The useful question is not whether an air-conditioner emits greenhouse gases. It does.

The question is how much global warming those emissions actually produce, when that warming occurs, and which practical choices reduce it most. Here we answer that question for one European residential split unit and for a stylised European fleet from 2026 to 2050 using a new metric: life cycle temperature response (LCTR).

FROM GWP TO TEMPERATURE RESPONSE

Global Warming Potential is indispensable for regulation and inventories, but it combines a gas's behaviour over a fixed horizon into one CO₂-equivalent number. That makes it difficult to see the difference between a relatively short-lived refrigerant pulse and CO₂ from electricity, which persists much longer. It also does not directly answer the most intuitive question: how much warmer is the world in a particular year?

The LCTR addresses this question. For each life-cycle emission, the gas, mass and year are recorded, and then the pulse is multiplied by its Absolute Global Temperature-change Potential (AGTP) for the remaining time to a chosen target year. AGTP is the IPCC's representation of the temperature change following an emission as an impulse response. Adding the responses from manufacturing, operation, and end-of-life handling gives the total warming contribution in the target year.

The results are expressed in picokelvin (pK, 10⁻¹² K) for a single unit, and in millikelvin (mK, 10⁻³ K) for a fleet. Figure 1 illustrates the process for an R32 unit installed in 2026 and retired in 2041. First, manufacturing CO₂ and refrigerant production occur; then, during service, annual electricity, ordinary leakage and the manufacture of replacement refrigerant follow; finally, in the retirement year, ordinary operation plus the unrecovered-charge release, equipment recycling and treatment of the recovered charge occur. As each R32 or CO₂ pulse follows its own AGTP curve, the total warming rises and later decays, rather than ending when the equipment is scrapped. Reading the curve in 2050 yields the LCTR. The calculation is deterministic and auditable: IPCC AR6 impulse responses and documented climate data feed a year-by-year mass-and-energy inventory; every flow retains its gas, date and source, and independent balance tests confirm that the source and life-cycle-stage totals reconcile.

The outputs should nevertheless be read as scenario results, not forecasts, because future stock, leakage, recovery and grid trajectories are explicit assumptions.

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WHAT DOES ONE AIR CONDITIONER ADD?

The representative unit is a 3.5 kW residential split system installed in 2026, used for 15 elapsed years and retired in 2041. The 2050 comparison holds capacity, lifetime, climate, leakage, recovery and grid pathway constant while changing only the refrigerant and associated performance data. For the R32 version, the corrected LCTR is 1.254 pK. Refrigerant release contributes 0.951 pK (75.8%), electricity contributes 0.220 pK, and embodied and service-related CO₂ contributes 0.083 pK. The last term includes equipment and initial-charge manufacture, production of replacement refrigerant, recycling, and treatment of the recovered charge. Refrigerant choice changes where the warming comes from (Figure 2). Under the same conditions, an R410A unit reaches 2.290 pK, an R454C unit 0.530 pK, and an R290 unit 0.291 pK. Moving from legacy R410A to propane therefore reduces the 2050 LCTR by a factor of 7.9. The direct warming contribution from propane is almost invisible, leaving electricity and embodied emissions as the residual. This is consistent with the very low GWP 100 value assigned to R290 in the EU's implementation information, whereas the restrictions for small split air-to-air systems tighten from GWP 150 in 2029 to fluorinated-gas prohibition in 2035, subject to safety exceptions. "European" here does not mean one particular city. The central result uses a synthetic stock-weighted climate: 60% of the mean cooling-temperature distribution for eight southern cities and 40% of the mean for six central cities, built from JRC PVGIS typical meteorological years. A city-level sensitivity check for the same R32 unit gives 1.05 pK in Munich and 1.81 pK in Seville, with the synthetic European value between them. The regional difference is mainly electricity use; the refrigerant and embodied terms are unchanged. The per-unit result is therefore representative of a defined European mix, not a universal value for every location.

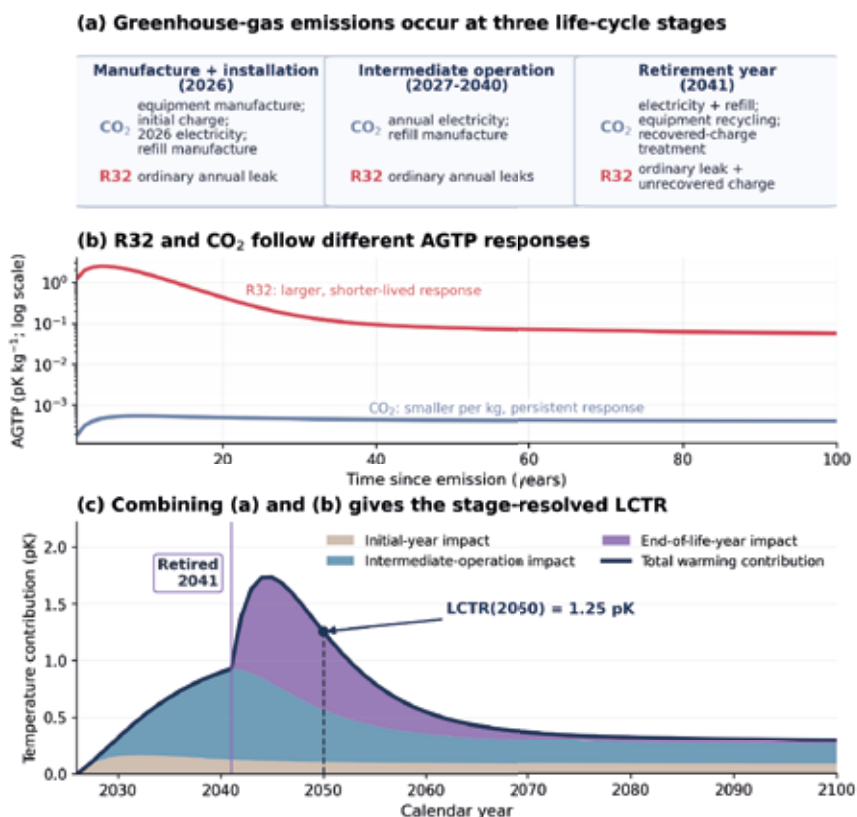


Figure 1: How LCTR converts a timed life cycle into a target-year temperature contribution, illustrated for a 3.5 kW R32 split unit installed in 2026, retired in 2041, operated under the regulated-baseline assumptions and a synthetic European climate. (a) CO₂ and R32 emissions occur during manufacture and installation, intermediate operation and the retirement year; 2041 includes ordinary leakage plus release of the unrecovered charge, while recovered refrigerant is treated. (b) AR6-based AGTP functions assign different time responses to each kilogram of R32 and CO₂. (c) Combining the dated emissions with their gas-specific AGTP functions gives the stage-resolved warming through 2100; their sum in 2050 is LCTR = 1.25 pK.

THREE EUROPEAN COOLING FUTURES

One pK is negligible; millions of units make the policy question visible. We therefore model an existing stock of 110 million residential split units and annual new sales from 2026 to 2050. The fleet stock and sales paths are scenario inputs, chosen to compare internally consistent futures rather than to predict the market. Existing units retire after 15 elapsed years, while new units enter with the refrigerant allowed by each scenario. Annual new sales rise from 8 to 16 million units in A and from 9 to 24 million in B and C; cumulative 2026-2050 new sales are therefore 300 million in A and 412.5 million in B and C. Grid intensity starts near the current EU level and then follows a fast, medium or stalled decline; the EEA documents both

the continuing EU decline and large differences among Member States. In the **Regulated Baseline (A)**, new units use R32 through 2028, R454C from 2029 to 2034 and R290 from 2035; annual leakage is 3.5%, end-of-life recovery is 50%, and the grid decarbonises at a medium pace. Its 2050 fleet LCTR is 0.185 mK. In the **Green Frontrunner (B)**, new sales move to R290 from 2027, annual leakage falls to 2%, recovery rises to 80%, efficiency improves and the grid decarbonises rapidly. B therefore has 37.5% more cumulative new sales than A, yet its 2050 LCTR is only 0.090 mK. In the **Fossil Laggard (C)**, the refrigerant schedule is the same minimum-compliance path as A; it is not an exemption-based extension of high-GWP refrigerants. The difference is poorer practice: 5.5% annual leakage, only 20% recovery, and a grid that remains more

carbon-intensive. With the same high uptake as B, its 2050 LCTR reaches 0.308 mK. Zhang et al. provide a useful check on the scale of these results. For global residential and commercial air-conditioning under SSP2-4.5, they estimate 113.3 GtCO₂e of cumulative emissions during 2010-2050 and an additional 0.05°C of warming in 2050 (range 0.03-0.07°C). Our sub-mK estimates cover only European residential split systems and emissions accounted after 2026, so the two studies are consistent in scale but are not directly comparable. Our three European values are tiny beside approximately 2°C of mid-century warming under an intermediate global pathway: 0.0045%, 0.0093% and 0.0154%, respectively. European residential cooling is therefore makes only a very small contribution to mid-century warming. But the C-B spread is 0.218 mK, larger than the whole Green Frontrunner footprint. Converting that spread to the mass of CO₂ that produces the same temperature response in 2050 gives about 446 Mt. This is a target-year temperature-equivalent comparison, not conventional cumulative CO₂e. Using the selected EDGAR 2023 fossil-CO₂ benchmark, it is about 7.3 times Austria's annual emissions.

WHAT DO THE NUMBERS ASK OF POLICY?

The first priority is a genuinely low-impact refrigerant, deployed as soon as safety rules, product design and installer competence allow. For small split systems, the EU timetable already points strongly toward that outcome. HFO blends can reduce direct warming during the transition, but climate performance is not their only environmental dimension. HFO-1234yf, a component of R454C, forms trifluoroacetic acid in the atmosphere, and both the scientific literature and the evolving European PFAS process justify continued scrutiny rather than assuming that low GWP settles every question. R290 is therefore especially important for small residential split systems and is already a practical option where charge limits, product design and installer competence

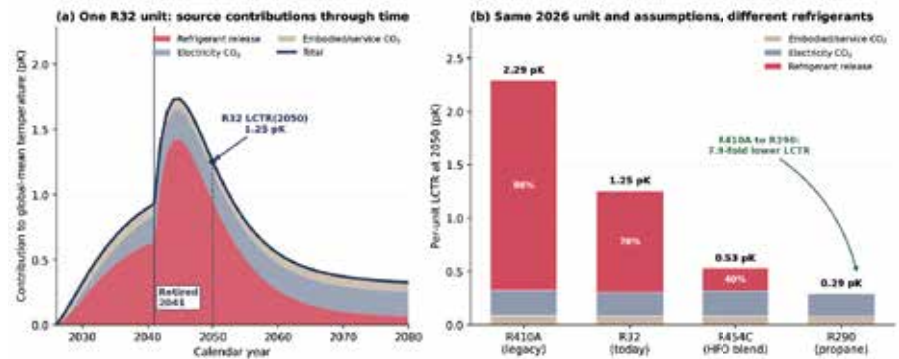


Figure 2: Source attribution of per-unit LCTR under common conditions: a 3.5 kW split unit installed in 2026, retired in 2041, regulated-baseline assumptions, synthetic European climate and 2050 target year. (a) The R32 case separates refrigerant release, electricity CO₂ and embodied/service CO₂ through 2080. (b) The corrected 2050 totals are 2.29 pK for R410A, 1.25 pK for R32, 0.53 pK for R454C and 0.29 pK for R290; percentages inside the bars are the refrigerant shares.

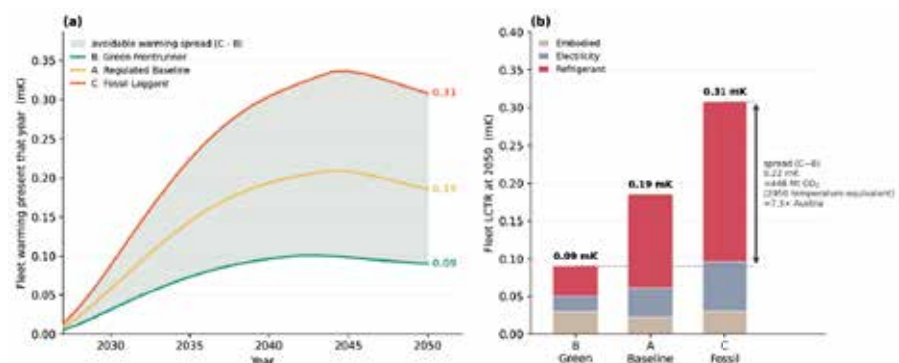


Figure 3: European residential split-air-conditioning fleet warming from emissions accounted after 2026. (a) Warming present in each evaluation year under the Green Frontrunner (B), Regulated Baseline (A) and Fossil Laggard (C); shading marks the avoidable C-B spread. (b) Refrigerant, electricity and embodied/service contributions in 2050 total 0.090, 0.185 and 0.308 mK. The 0.218 mK C-B spread is about 446 Mt of CO₂ on a 2050 temperature-equivalent basis, or 7.3 times Austria's selected 2023 annual fossil-CO₂ benchmark.

allow it to be used safely. The second priority is end-of-life handling. The unrecovered fraction is a direct release; the recovered fraction is the amount sent for treatment. Better recovery therefore reduces the largest single refrigerant pulse. Preventing service leaks also avoids both the direct emission and the manufacturing footprint of replacement refrigerant. The third priority is electricity decarbonisation. As direct refrigerant warming approaches zero, efficiency, passive cooling, sensible setpoints and grid decarbonisation dominate what remains. The conclusion is not that Europe should deny cooling. It is that access and climate protection can be aligned: use the lowest-impact refrigerant that can be applied safely,

keep it inside the system, recover it at retirement, and reduce the carbon behind the plug.

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Mobile Air Conditioning in Europe Vehicles Electrification and System Evolution



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The Mobile Air Conditioning (MAC) system role and functions are evolving due to the environmental regulations that are leading to the full decarbonization, in a context where the global vehicle fleet is projected to reach up to 2 billion by 2040 with a progressive increase of road vehicle electrification. In this context MAC systems are expected to contribute significantly to greenhouse gas (GHG) emissions. This evolution demands a deeper integration of the MAC with the systems of the vehicle to contribute to the whole vehicle energy efficiency increase. This evolution increases significantly complexity and places a strong emphasis on energy efficiency, as thermal management performance directly influences vehicle range and overall environmental benefits. Consequently, the skills and competences required for designing, manufacturing, installing and maintaining the new vehicle thermal system are evolving coherently with the system evolution. In addition, currently used refrigerants (HFC-134a and HFO-1234yf) are in discussion for their environmental compatibility (GWP and PFAS) and at risk of ban or use limitation. In response to all these facts, the industry is re-evaluating alternative refrigerants: natural refrigerants such as CO₂ (R-744) and propane (R-290) offer advantages in terms of environmental sustainability, low or negligible GWP, and independence from patent constraints.

MOBILE AIR CONDITIONING AND VEHICLE ELECTRIFICATION

With the progressive electrification of vehicles, mobile air conditioning and vehicle thermal management systems are evolving towards the so-called Integrated Thermal

Management System. The Hybrid Electric Vehicle (HEV/PHEV) have an internal combustion engine (ICE) combined with an electric motor and battery enabling the vehicle to travel in pure electric distances, function of the battery size and the possibility to recharge it (PHEV). The MAC is part of the vehicle thermal system that must also serve the battery, motor, and thermal controller and uses electrically driven compressor. In Battery Electric Vehicles (BEV), thermal management is of paramount importance because heating and cooling is strongly affecting the electric range and because battery performance and lifetime depend on thermal conditions. Recently, the heat pump system to provide both heating and cooling, has become the most used approach because of its higher efficiency in ensuring the heating. The refrigerant charge is usually about 30 to 50 % higher than that in a conventional AC system function of the technology selected to cool the battery (indirect or direct expansion). Indirect expansion and condensation (i.e., liquid cooled condensers and liquid heated evaporators) enable lower refrigerant charge, higher system flexibility and safe use of natural flammable refrigerant (R-290).

The vehicle electrification is progressing quite rapidly in Europe for passenger cars while is a bit slower for vans and not started for heavy duty and other kinds of vehicles due to the limitations of current battery technology (battery density).

EVOLUTION OF COMPETENCIES IN AUTOMOTIVE THERMAL SYSTEMS

The road-vehicle electrification and with this the software-defined

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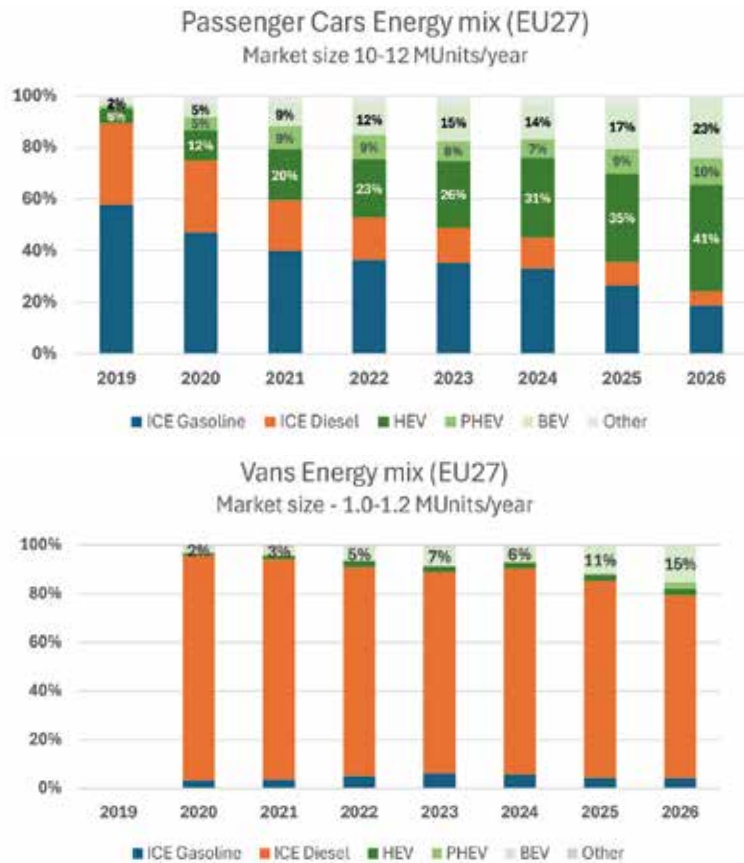


Figure 1: The European Passenger cars market electrification is progressing rapidly.

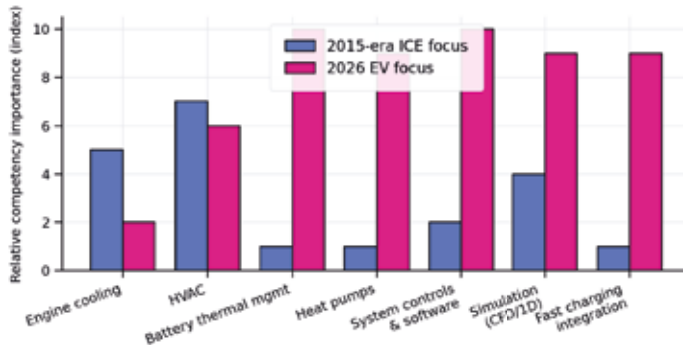


Figure 2: Evolution of Automotive Thermal-System Competencies (illustrative synthesis).

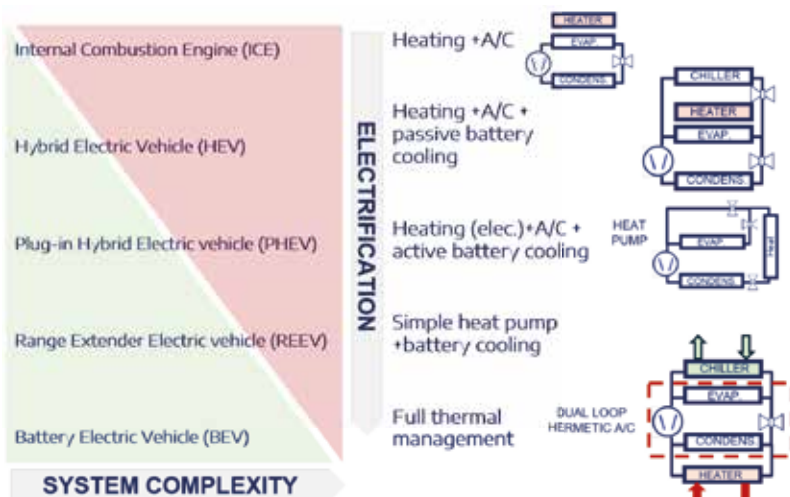


Figure 3: Evolution of Vehicle Thermal Systems.

vehicle architectures, fast charging requirements and stringent efficiency targets are leading to the transformation of the automotive thermal engineering. Therefore, also the competencies and skills are evolving, and new profiles are required by automotive manufacturers, suppliers and engineering service providers. Traditional automotive thermal systems focused on engine cooling and cabin HVAC. The rapid adoption of electrified powertrains has shifted engineering priorities toward battery thermal management, integrated thermal architectures, heat pumps, advanced controls and simulation-driven development. Key drivers include EV adoption, battery safety, charging performance, energy efficiency, sustainability requirements and low-GWP refrigerants. Thermal engineering is increasingly multidisciplinary. Core growth areas include battery thermal management, vehicle thermal management systems, heat pumps, model-based controls, CFD/1D simulation, digital twins and AI-supported energy management.

Figure 2 summarizes, qualitatively, the relative shift in engineering emphasis from the 2015 ICE-oriented environment to the current EV-centric environment. The thermal engineer is evolving from a component specialist into a vehicle energy-management specialist. Future competitive advantage will depend on combining thermal expertise with software, controls and systems engineering competencies. Battery thermal management, integrated thermal architectures, heat pumps, software controls and virtual engineering represent the fastest-growing competencies through 2030.

MAINTENANCE AND SERVICING

The electrification of light-duty vehicles has significantly transformed mobile air conditioning (MAC) maintenance and service (Figure 3). While the basic refrigeration cycle remains unchanged, HVAC systems have evolved from standalone comfort features into critical thermal-management systems that support cabin conditioning,

battery temperature control, power electronics cooling, and charging performance.

Modern hybrid and battery electric vehicles increasingly use high-voltage electric compressors instead of engine-driven units, requiring technicians to follow strict electrical safety procedures and acquire expertise in inverter-controlled compressor technology. In addition, the widespread adoption of heat pump systems has introduced more complex refrigerant circuits, valves, sensors, and control strategies that demand advanced diagnostic capabilities. The transition to low-global-warming-potential refrigerants, particularly to R-1234yf, has also driven the need for specialized recovery, recycling, leak-detection, and charging equipment. Probably the next transition to natural refrigerants as consequence of PFAS issue will ask for another change for adapting the technologies and skills to new refrigerants (e.g. R-290 flammable, R-744 high pressure). Another important change is the use of dielectric compressor oils, where contamination can lead to compressor failure or electrical insulation issues. Consequently, HVAC servicing now relies heavily on software-based diagnostics, electronic expansion valves, thermal controllers, and OEM diagnostic tools. As vehicle electrification continues to expand, technicians must combine traditional air conditioning expertise with knowledge of high-voltage systems, battery thermal management, electronics, and digital diagnostics. Overall, MAC service is becoming increasingly sophisticated, safety-critical, and strategically important for vehicle efficiency, range, reliability, and CO₂ reduction objectives.

REFRIGERANTS, ENVIRONMENTAL REGULATION AND NATURAL ALTERNATIVES

Currently used refrigerants such as R-134a and R-1234yf are facing increasing environmental and regulatory scrutiny. R-134a is affected by the progressive HFC phase-down due to its high global warming potential. R-1234yf, despite

Refrigerant option	Main advantages	Main engineering constraints	Implications for MAC/thermal design
HFC-134a	Known technology and established service infrastructure.	High GWP and HFC phase-down pressure.	Limited long-term attractiveness for new platforms in regulated regions.
HFO-1234yf	Low GWP and broad current adoption in passenger-car MAC systems.	PFAS-related regulatory scrutiny and environmental persistence discussions.	Requires monitoring of regulatory evolution and end-of-life considerations.
R-744 (Carbon Dioxide)	Natural refrigerant, very low GWP and non-flammable.	Very high operating pressure and demanding component/control requirements.	Requires dedicated high-pressure architecture, components, servicing equipment and safety procedures.
HC-290 (Propane)	Natural refrigerant, very low GWP and favourable thermodynamic performance.	High flammability, charge limitation and leakage-risk management.	May benefit from indirect architectures, reduced charge, careful component isolation and dedicated servicing rules.

Table 1: Refrigerant option (not exhaustive).

its low-GWP, is being discussed in the broader context of PFAS-related regulatory initiatives and end-of-life degradation concerns. This evolving regulatory landscape is pushing the industry to assess natural refrigerants such as CO₂ (R-744) and propane (R-290), which offer very low GWP and reduced dependency on fluorinated refrigerant supply chains.

CONCLUSIONS

The Mobile Air conditioning system is facing again an evolutionary phase driven by the need to further reduce its direct and indirect environmental impact. The road vehicles electrification is impacting vehicle architecture, refrigerant system

design, and the type and quantity of refrigerant used and introducing new approaches to integrated thermal management. Integrated systems for combined heating and cooling, as heat pumps and dual loop heat pumps can improve energy efficiency. New skills and wider competence profiles are required for engineers and technicians involved in design, production, servicing and maintenance to deal with the transition from simple air conditioning system to the more complex thermal management system. Finally, in case PFAS-related issue that could lead at least in Europe to ban or limitation on currently used refrigerants, R-744 and HC-290 are the mainstream alternatives.



Renowned international expert Max Vanderhenst recently led a comprehensive four-day technical training course in Cairo, Egypt, focusing on the latest advancements in Mobile Air Conditioning (MAC) and vehicle thermal management. Organized by Centro Studi Galileo (CSG) and UNIDO, the program brought together 50 local specialists to advance sustainable automotive refrigeration. The curriculum highlighted the transition to eco-friendly alternatives, including hydrocarbons and CO₂.

European Innovation Council Pathfinder

Portfolio of Projects: Breakthrough Innovations in Europe for a Sustainable Cooling Transition



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CoCoMag project, Oliver Gutfleisch, TU Darmstadt

ColteraTREC project, Krassen Dimitrov, Voltera Bulgaria; Christine Minke, Clausthal University of Technology

COOLPOL project, Emmanuel Defay, Luxembourg Institute of Science and Technology

DYMAN project, Walter Mittelbach, Sorption Technologies GmbH

Frostbit project, Patrick Rosa, Université de Bordeaux and CNRS-Bordeaux INP; Helena Shepherd, University of Kent

HYDROCOOL project, Joan Carles Bruno and Alberto Coronas, Universitat Rovira i Virgili

LEMON project, Alexander Regnat and Steffen Säubert, Kiutra GmbH

MAGCCINE project, João Belo, Universidade do Porto; Victorino Franco, University of Seville

SMACool project, Paul Motzki, Saarland University; Jaka Tušek, University of Ljubljana

INTRODUCTION

From a historical perspective, the Montreal Protocol on substances that deplete the Ozone layer, which came into effect in 1989, has deeply shaped the refrigeration and air conditioning (RAC) sectors across building, industrial, and transport applications. By the late 1990s, the dominant vapor-compression technology relied heavily on synthetic refrigerants, mainly chlorofluorocarbons (CFCs). The imperative to halt stratospheric ozone depletion drove a first migration toward hydrochlorofluorocarbons (HCFCs) and, subsequently, hydrofluorocarbons (HFCs). The latter were later targeted by further regulations due to their high Global Warming Potential (GWP) measured over a 100-year horizon.

The Kigali Amendment to the Montreal Protocol came into effect in 2019 and established a pathway for the global transition to phase down high-GWP HFCs, fostering the adoption of low-GWP options, including hydrofluoroolefins (HFOs) and, notably, natural refrigerants (CO₂, hydrocarbons, ammonia) which offer near-zero direct environmental impact. Europe accelerated this trajectory through the 2024 F-Gas Regulation, imposing stricter reduction thresholds than those mandated by the Kigali Amendment while aligning with emerging environmental frameworks such as potential PFAS restrictions. As vapor-compression systems progressively transition to natural fluids, direct emissions from refrigerant leakage are minimized, shifting the strategic focus toward reducing indirect emissions linked to energy consumption. In line with EU decarbonization and electrification policies — such as the 2026 Electrification

Act and the Energy Performance of Buildings Directive (EPBD) — the main challenge becomes lowering energy consumption while meeting required thermal capacities under target ambient and indoor conditions. Within this evolving context, alternative not-in-kind (NIK) technologies—including solid-state caloric systems (magneto-, baro-, electro-, and elastocaloric), sorption, and thermo-mechanical systems do not aim to directly compete with natural refrigerants in standard applications, but represent strategic solutions where vapor compression encounters physical, operational, or safety boundaries. These boundary conditions include ultra-low temperature regimes (below -60 °C down to cryogenic levels, where most conventional refrigerants freeze), high-hazard environments prohibiting flammable or toxic working fluids (e.g., confined spaces, aerospace, or environments with spark risks), and applications operating across narrow temperature spans (<10 K). Furthermore, advanced NIK and sorption paradigms seamlessly integrate with smart energy management architectures, enabling efficient thermal energy storage and the recovery of waste heat, such as in high-performance data centers. This comprehensive landscape of technological opportunities defines the key levers needed to surpass the current state of the art and drive a sustainable cooling transition.

Within this framework, the technologies presented in this paper were selected under the EIC Pathfinder Challenge call “Clean and Efficient Cooling”, managed by the European Innovation Council and SMEs Executive Agency (EISMEA). The core objective of the call was to build a direct bridge between cutting-edge European

environmental policies—including minimum performance requirements under the Ecodesign for Sustainable Products Regulation, 2050 climate targets (implicitly aligned with Kigali and the 2024 F-Gas Regulation), and the 2023 EPBD. The EIC Pathfinder Challenge aims to unlock breakthrough, high-risk/high-impact technologies, allowing Europe—supported by its strong, high-tech industrial base—to advance its leadership in the deep-tech sector. Beyond individual project developments, the initiative is characterized by a coordinated portfolio approach. Based on a shared vision among the EIC Program Manager, Project Officers, and the scientific-industrial ecosystem formed by the participants, this model fosters mutual reinforcement and maximizes the collective impact of the projects.

The following sections provide a detailed overview of these emerging technologies and their underlying physical principles, outline their targeted socio-economic and environmental impacts, and describe the portfolio strategy and joint activities carried out by the Portfolio Working Groups. An overview of the portfolio projects can be found on the portfolio website.

SECTION 1: THEMATIC AREAS AND WORKING PRINCIPLES OF THE DIFFERENT TECHNOLOGIES

Cooling systems (and, reversibly, heating systems) transfer thermal energy from a lower-temperature source to a higher-temperature sink. This process cannot occur spontaneously, as heat naturally flows from a hotter to a colder body. Therefore, a working medium (gaseous, liquid, undergoing a liquid-vapor phase transition, or solid) must operate at a temperature lower than the cold source during the heat absorption phase and, conversely, at a temperature higher than the hot sink during the heat rejection phase. Theoretically, this is achieved through ideal thermodynamic cycles with no internal or external irreversibilities: the Carnot cycle for sources with

infinite heat capacity, or the Lorenz cycle for sources with finite heat capacity.

Vapor-compression technology approximates these ideal cycles by performing heat exchange through a refrigerant undergoing a liquid-vapor phase change, thus enabling near-isothermal processes. For practical and economic simplicity, real cycles implement expansion via a dissipative throttling process and restrict compression to the vapor phase to avoid liquid-induced compressor damage. Operating with a phase-changing refrigerant provides a large volumetric cooling capacity and exceptional heat transfer performance, significantly reducing equipment size. Today, vapor-compression technology is extremely mature, mass-manufactured, highly cost-effective, and scaled globally across virtually all cooling capacities. The sector is actively adapting to environmental mandates by transitioning toward non-ozone depleting and ultra-low-GWP natural refrigerants. Further performance enhancements are centered on improving operational resilience over the equipment lifecycle, which is a key objective addressed by one of the Portfolio projects presented herein (BEYOND).

However, as highlighted in the Introduction, specific contextual constraints (e.g., extreme operating temperatures, safety restrictions regarding flammable/toxic fluids, or narrow temperature spans) can render conventional vapor compression less effective or impractical, opening the door for alternative not-in-kind technologies. A brief description of the working principle of each technology is reported below and schematized in Figure 1.

Thermomechanical Isothermal Compression (TIC) is a novel concept related to the well-established principle of thermochemical compression, in which the conventional mechanical compressor is replaced by a liquid piston compressor (LPC). Compression is a critical process

in vapor-compression systems and can account for a significant fraction of their total energy consumption. Consequently, the development of more energy-efficient compression technologies is becoming increasingly important in response to the growing demand for heating and cooling across a wide range of applications. In conventional rapid gas compression, a significant fraction of the mechanical work supplied to the compressor is converted into an increase in the refrigerant temperature. This temperature rise increases the compression work and may also adversely affect the efficiency and operating conditions of the overall system. From a thermodynamic perspective, isothermal compression represents the theoretical minimum mechanical work required to compress a gas between two specified pressure levels, as heat is continuously rejected from the gas during compression to maintain a constant temperature. Liquid piston compression offers a promising approach to achieving near-isothermal compression. In an LPC, a liquid is used as the compression medium to reduce the gas volume within a fixed compression chamber. Because the liquid piston can provide a large gas–liquid interface and eliminates the need for conventional mechanical sliding seals, this configuration can potentially reduce frictional losses, lubrication requirements, and refrigerant leakage. More importantly, the intimate contact between the gas and the liquid can enhance heat transfer during compression, allowing the compression process to approach the isothermal limit. The extent to which near-isothermal compression can be achieved in an LPC depends primarily on the ability to remove the heat generated during compression. This can be enhanced through three main strategies: (i) maximizing the heat-transfer area available within the compression chamber, (ii) increasing the time available for heat transfer during the compression process, and (iii) improving the thermophysical and heat-transfer properties of the compression liquid.

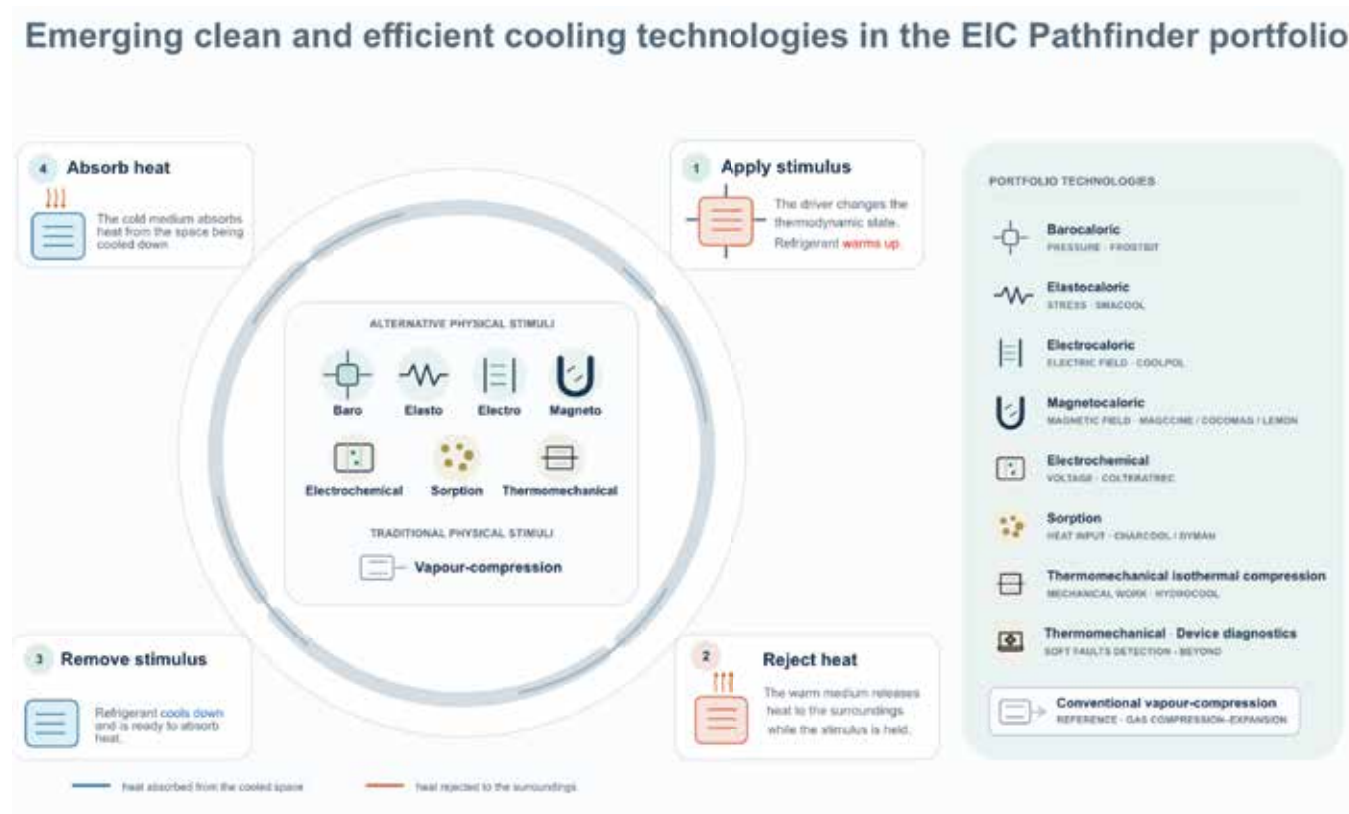


Figure 1: Schematic representation of the traditional and alternative clean and efficient cooling technologies explored within the EIC Pathfinder portfolio, illustrating their alternative physical stimuli and their implementation within a common four-step thermodynamic cooling cycle: stimulus application, heat rejection, stimulus removal, and heat absorption.

The Thermomechanical Isothermal Compression concept using liquid piston technology, provides a potential alternative to conventional mechanical compression in vapor-compression systems.

The Thermally Regenerative Electrochemical Cycle (TREC)

provides a mechanism for directly coupling heat flows to electrochemical processes. The cycle operates on the principle that certain electrochemical reactions proceed with a significant change in entropy, causing their reversible electrode redox potentials (V) to be highly temperature-dependent. For a single-electron transfer, the temperature coefficient is defined as $\alpha_T = \frac{dV}{dT} = \frac{\Delta S}{F}$, where F is the Faraday constant. A complete TREC involves executing an electrochemical forward reaction at a specific temperature, followed by the regeneration of the redox reactants via a reverse reaction at a different temperature. This fundamental voltage-temperature dependency allows the system to either harvest electricity from a

temperature differential or pump heat against a temperature gradient. When operated in this heat-pump mode, the cycle absorbs thermal energy from a cold environment during the endothermic reaction and discharges it to a hotter environment during the exothermic phase. This configuration enables TREC to function as a highly efficient cooling technology that approximates an ideal reverse Carnot cycle, entirely eliminating the need for mechanical vapor compression and refrigerant phase-changes.

Sorption cooling exploits the reversible sorption and desorption of a refrigerant onto or into a solid or liquid sorbent material, using low-grade heat rather than mechanical compression as the driving energy. Two main technology families exist: adsorption systems use solid sorbents such as silica gel, zeolite, or activated carbon, to adsorb/desorb water vapor, in intermittently cycled beds; absorption systems, on the other hand, use a liquid sorbent/sorbate pair, most commonly lithium

bromide-water or ammonia-water, operating in a continuous cycle. In both cases, an external driving heat source regenerates the sorbent by desorbing the refrigerant, which is then condensed and re-evaporated to produce the useful cooling effect, while the sorbent's re-uptake of refrigerant vapor releases heat during the sorption phase. Because the cycle is heat-driven rather than electricity-driven, sorption cooling is particularly well suited to valorizing waste heat or solar thermal energy and since water is used as refrigerant, it can operate with zero ozone-depletion potential and zero global warming potential. Current R&D challenges center on improving heat and mass transfer within the sorbent bed to raise cycle frequency and power density, reducing system size and weight to improve compactness, and enabling efficient operation at lower driving temperatures to widen the range of usable waste-heat sources.

Caloric cooling technologies change the paradigm, from the volume change of a gas to the order/

disorder of a solid. Depending on the driving force that creates the order and the characteristic of the solid that changes its configuration (or the magnitude that changes its value), we will deal with magneto-, baro-, elasto-, electro-caloric, etc. The magnetocaloric effect is driven by an adiabatic (fast) application/removal of magnetic field, with the temperature change being associated to the change in magnetization via the order/disorder of magnetic moments. A magnetic refrigeration cycle utilizes alternating magnetization and demagnetization steps, interleaved with heat exchange steps between a cold load (refrigerated space) and a hot sink (ambient environment). To achieve a large magnetocaloric response, the material should exhibit a significant and abrupt change of magnetization with temperature. The material design/selection strategy depends heavily on the operating temperature regime. At cryogenic temperatures, paramagnetic salts are effective due to the divergence of their magnetic susceptibility near absolute zero. Near room temperature, relevant for commercial refrigeration and air conditioning, sharp magnetization changes require phase transitions. These can be second-order thermomagnetic transitions with zero thermal hysteresis (e.g., elemental Gd) or giant first-order magnetostructural/magnetoelastic transitions (e.g., $\text{Gd}_5(\text{Si}, \text{Ge})_4$, $\text{La}(\text{Fe}, \text{Si})_{13}$, or $\text{MnFe}(\text{P}, \text{As})$ families). Current R&D challenges center on suppressing thermal hysteresis in first-order materials, designing cost-effective and compact magnetic field application subsystems, optimizing heat transfer inside active magnetic regenerators (AMRs), and achieving seamless system integration for large real-world coefficient of performance (COP).

Electrocaloric materials experience reversible variations of temperature when an external voltage is applied. A rapid change of voltage (blue signal) induces an adiabatic temperature change ΔT_{ad} . The latter is generally positive, though some materials can experience an opposite electrocaloric

effect, depending on the nature of the phase transition involved. If one keeps voltage on for some time, the generated heat dissipates into the surroundings, which causes the temperature to return to its initial value, provided that the material has negligible leakage current to prevent the Joule heating effect. If voltage is then removed abruptly, the material experiences the opposite variation of temperature, below the initial temperature, which suggests that a cooling device could be prepared out of such materials. The prototypical electrocaloric materials are 1) perovskite ceramics like lead scandium tantalate or barium titanate and 2) polyvinylidene difluoride (PVDF) and its derivatives. These materials exhibit adiabatic variations of temperature of a few degrees that are generally not large enough to directly address applications. There are two main devices used to enlarge the overall variation of temperature, namely 1) cascaded devices working under the “pass-the-parcel” principle – a succession of electrocaloric elements that are activated successively after having shared their heat with the next stage and 2) regenerators, in which a heat-transporting fluid is associated with the electrocaloric elements to accumulate the heat and the cold in two different regions of the device. The best results obtained so far in the literature are a device temperature span of 14.2 K and cooling power of 0.77 W obtained with a cascaded design of six PVDF cooling capacitors and a device temperature span of 21 K and a cooling power of 2.1 W obtained with a regenerator design based on lead scandium tantalate.

Mechanocalorics effects lie upon the mechanical response (strain) of a solid to an external stress. The elastocaloric effect is characterized by typically uniaxial stress, while for the barocaloric effect this stress comes equally from all directions (isotropically, meaning hydrostatic pressure).

The **barocaloric effect** is conceptually the closest to standard vapour compression

technology. Indeed, the structural response of barocaloric materials to the external stress (hydrostatic pressure) is characterized by a substantial change of volume, often corresponding to a structural phase transition. This translates into a significant change of entropy (order), which may reach values close to the liquid-gas phase transition phase values of fluids used in HVAC. The technology would thus work through adiabatic (fast) compression of the active material to its more ordered low-volume phase (liquid-like state, step 1 in Figure 1), thermal exchange with the heat sink (step 2), adiabatic decompression to the more disordered high-volume phase (gas-like state, step 3), and thermal exchange with the thermal load (step 4) to complete the refrigeration cycle. To achieve the best performance, an ideal barocaloric material should address the following requirements: 1) large values of isothermal entropy variation (DS) and adiabatic temperature change (DT) upon pressure application; 2) activity over the largest temperature span possible around the temperature of interest (e.g. room temperature for standard refrigeration applications); 3) small or no hysteretic behavior, to avoid unnecessary work to drive the effect; 4) being effective in low pressure ranges, to avoid heavy pressure vessels and allow the use of off-the-shelf compressors; 5) high thermal conductivity, to increase as much as possible the operating frequency; 6) safety (low toxicity and flammability); 7) easy shaping of the material to optimize heat exchange; 8) physical and chemical stability, in particular respective to pressure-transmitting and heat-transfer media, and cyclability over millions of cycles with limited performance degradation due to fatigue; 9) cost competitiveness, scalable and easy synthesis, absence of CRMs. Barocaloric technology is a young and currently immature technology. Current R&D efforts thus focus on the design of both the barocaloric materials themselves and also on the development of devices. On one hand, investigation into various families of barocaloric materials

tries to find or design one with optimum properties. Among the most promising barocaloric materials currently under investigation are polymers, spin-crossover molecular complexes, hybrid organic-inorganic materials, and plastic crystals. In polymers, giant barocaloric effects arise because applied pressure restricts molecular interactions.

Spin-crossover molecular complexes exhibit two magnetic states that can be switched by changes in temperature or pressure, producing large entropy changes through molecular vibrations associated with the structural phase transition.

In hybrid organic-inorganic materials, the entropy change originates from the restriction of rotational, translational, orientational, and conformational degrees of freedom under applied pressure. In plastic crystals, the entropy change results from the loss of orientational degrees of freedom during the transition between an ordered solid phase and a plastic (liquid crystal-like) mesophase.

On the other hand, investigation into practical devices focuses mainly on the design of optimized heat exchangers, and on recovery of the work necessary to apply the required pressure.

Elastocalorics is based on the unusual heating and cooling properties of so-called Shape Memory Alloys (SMA) from, e.g., Nickel-Titanium (NiTi). Simple mechanical loading and unloading of superelastic SMAs releases or absorbs large amounts of latent heat due to a reversible stress-induced, solid-state martensitic transformation in the crystal lattice structure. Even with currently available materials, originally developed for biomedical applications, temperature changes of up to ± 20 K can be generated. The increasing attention of the technology is motivated by promising developments in material Coefficients of Performance, COP_{mat} (i.e., ratio between the material's latent heat and hysteresis losses) with values of over 30, which potentially could lead at a drastic increase in efficiency compared to recommended target

(MEPS) values in reference to split HVAC devices. In the current state of research, several functional devices demonstrated that it is possible to develop a fatigue-resistant ElastoCaloric (EC) cooling/heating device (above 1 million cycles) with a temperature span above 30 K. With thin structures, specific cooling powers of up to 5-10 kW/kg of EC material are possible. Fatigue-resistant operation with more than 10 million loading cycles has been demonstrated without significant degradation of EC effect or failure of EC material. In summary, over the last decade research has focused on first proofs-of-concept in generic system demonstrators but there have been very few efforts of EC systems for specific commercial applications and the associated requirements. Almost no research at all has looked at the aspect of specific drive technology in EC systems, making all developments today reliant on commercially available electric or even hydraulic drives, which drastically limits the possible fields of applications as the documented specific powers on material level do not translate to system level.

SECTION 2: INNOVATION TARGETED BY EACH PROJECT WITH RESPECT TO THE CHALLENGES

BEYOND – Resilient Vapor-Compression Systems through Indirect Fault Detection

Small-capacity vapor-compression systems, such as those used in residential and automotive applications, typically operate over a useful lifetime of 10 to 12 years. Over this period, unaddressed soft faults—most notably minor refrigerant leakages—frequently go unnoticed by end users while causing energy efficiency degradations of up to 20% within just four years. Rather than focusing on conventional predictive maintenance, the BEYOND project aims to enhance operational resilience by accurately identifying and diagnosing these subtle operational faults. Diagnosing soft faults presents a fundamental reverse-engineering challenge with

no direct analytical solution. BEYOND addresses this hurdle by developing a novel diagnostic algorithm that relies exclusively on indirect, cost-effective measurements. To achieve this, rigorous experimental campaigns are combined with validated, high-fidelity physical models to build a comprehensive synthetic dataset for algorithmic training and validation.

As a proof of concept, BEYOND demonstrates the real-world viability of this indirect diagnostic approach. Once validated, this methodology can be deployed across millions of small-scale cooling and heat pump units worldwide. By maintaining optimal energy performance throughout the equipment lifecycle, BEYOND ensures compliance with minimum energy efficiency standards and directly supports global decarbonization targets under the Kigali Amendment framework.

CharCool - Rethinking the future of clean cooling through a revolutionary class of thermally-driven chiller based on a novel bio-based thermochemical material:

Europe needs to cut carbon emissions and ensure stable energy supply, particularly in cooling technologies that currently rely heavily on electricity. To tackle these challenges, the EIC-funded CharCool project uses natural energy and nature-based methods to create a sustainable cooling system. It stores excess renewable energy or waste heat for seasonal use, aiming to transform the cooling industry with a flexible, reliable, and eco-friendly alternative to traditional methods. This initiative aims to revolutionise the cooling industry by offering a flexible, reliable, and environmentally friendly alternative to conventional methods. Projected to cut current sorption system volumes and costs by 40% and 50% respectively, CharCool enhances cooling efficiency but also promises significant economic and social benefits.

CoCoMag - Multi-property Compositionally Complex Magnets for Advanced Energy Applications:

For over a century, technologies such as gas-compression cooling

and traditional magnet design have seen incremental improvements. As we transition to a net-zero future, the demand for high-performance magnets in applications like electric vehicles and magnetic refrigeration is skyrocketing. However, these technologies heavily rely on rare and critical materials such as cobalt and rare earths, which are costly and unsustainable. The EIC-funded CoCoMag project plans to use compositionally complex alloys (CCAs) to develop permanent magnets and magnetocaloric materials. Unlike conventional alloys, CCAs avoid the need for critical materials and combine multiple elements in ways that optimise durability and efficiency.

ColteraTREC

The ColteraTREC system advances traditional TREC concepts by utilizing entirely aqueous liquid electrolytes with soluble electroactive reactants, replacing conventional solid electrodes.

This liquid-based architecture enables continuous recirculating operation, highly efficient heat transfer, and optimal heat regeneration through counter-flow liquid-to-liquid heat exchangers. The core system functions equivalently to a combination of two Flow Batteries (FBs) operating at different temperatures. It utilizes two distinct electrolytes, EL1 and EL2, characterized by half-cell reactions with significant and opposing temperature coefficients α_T . Specifically, the hexacyanoferrate reaction ($\text{Fe(CN)}_6^{3-} + e^- \rightleftharpoons \text{Fe(CN)}_6^{4-}$) exhibits a negative α_T , while the copper reaction ($\text{Cu}^{2+} + e^- \rightleftharpoons \text{Cu}^+$) exhibits a positive α_T . By combining these reactions, ColteraTREC achieves a cumulative full-cell α_T exceeding 3.4 mV/K, which significantly minimizes internal resistance losses and maximizes overall power density. The system employs two isothermal electrode stacks connected electrically in series, allowing the circulating electrolytes to absorb heat in a cold environment and reject it in a hot environment. Furthermore, the architecture is supported by low-cost, self-healing ion-permeable membranes based on hexacyanoferrate coordination

polymers. Heat regeneration is managed by lightweight, “breathable” heat exchangers using non-wettable porous polyolefin membranes, which facilitate rapid temperature equilibration via evaporative mass and heat transfer. Technology development and scale-up are closely monitored through prospective environmental life cycle assessment (pLCA) to achieve the targeted sustainable cooling transition.

COOLPOL

The idea of this project is to combine the exclusive assets of electrocaloric polymers in one single device and assess its global efficiency. These assets are (1) excellent electrocaloric properties, (2) the possibility to boost efficiency by recycling electric energy, (3) scale-up possibilities thanks to roll-to-roll technique and (4) intrinsic compactness due to the small size of electric power supply devices. More specifically, the project aims to make polymer-based electrocaloric multilayers capacitors and introduce them in regenerators. This technique gave excellent results with ceramics and modelling tells us that these results should be even better with such polymers. We will then develop four new innovative technologies, namely 1) enhanced electrocaloric polymers via chemical functionalization, 2) electrocaloric polymer-based multilayer capacitors, 3) fluid-assisted polymer-based electrocaloric regenerators and 4) recycling of the electric energy used to trigger the electrocaloric effect.

DYMAN – DYnamically MANaged self-cooling HPC Data Centers.

DYMAN develops a new generation of adsorption chillers purpose-built for cooling High Performance Computing (HPC) data centres, replacing today’s electrically driven, compression-based cooling with a heat-driven sorption cycle.

What sets the technologies developed with the project apart from conventional adsorption chillers (typically bulky, slow-cycling units designed for steady industrial or district-cooling loads) is its dynamic management capability: a Digital Twin combined with AI-based

predictive control allows the chiller to anticipate and respond in real time to the data center’s fast, highly variable computational load, rather than operating at the fixed set-point typical of existing sorption cooling installations. The project contributes with novel adsorbent materials and 3D-printed components that shorten cycle times and increase power density and compactness beyond what conventional systems achieve, while enabling efficient operation at the low driving temperatures typical of recovered waste heat from Data Centers, insufficient for most commercial sorption units to exploit. By replacing electrically driven compression cooling systems with this heat-driven, dynamically managed sorption chiller, DYMAN targets a substantial reduction in data center cooling electricity demand.

The **FROSTBIT** project is developing the world’s first regenerative barocaloric cooling device based on spin crossover materials, which undergo an electronic phase transition. One of the key advantages of spin crossover materials is their versatility.

Their barocaloric response can be tailored to operate across an exceptionally wide temperature range: from extreme cryogenic temperatures to well above room temperature.

This opens up opportunities beyond conventional refrigeration, enabling the development of alternative, not-in-kind cooling technologies for applications spanning scientific instrumentation, quantum technologies, aerospace, medical systems, electronics cooling, and industrial thermal management. Bringing together eight partners from across the EU and the UK, FROSTBIT combines expertise in materials science, chemistry, physics, engineering, and device development.

The consortium is addressing every stage of the technology development process, from the environmentally friendly synthesis and scalable shaping of spin crossover materials to the comprehensive characterization of their phase behaviour,

thermodynamic properties, and cooling performance under operating conditions.

The project will culminate in the design, construction, and demonstration of a prototype regenerative barocaloric cooling device, laying the foundation for a new class of solid-state cooling solutions across a diverse range of temperature regimes and applications.

This prototype will target an initial cooling power of 100 W at room temperatures and will provide a temperature span of at least 20 K with a target COP between 4 and 6 (corresponding to 30% of Carnot efficiency). Scalability is still under investigation, so initial sectors targeted are small-scale refrigeration (household appliances). Interestingly, barocaloric refrigeration is the one technology that could be mixed easily with standard HVAC refrigeration, and a sector of interest where HVAC meets difficulties is very low temperature refrigeration, useful for medicine preservation, biological specimens preservation or CO₂ trapping. n-pentane (R601) is currently used as HFC substitute in a variety of refrigeration systems. It is also a very good pressure-transmitting medium down to low temperatures, so the project has started considering mixed systems using solid-state barocaloric refrigeration and pentane.

HYDROCOOL - Novel advanced hydraulic CO₂ refrigeration system for multiple sectors: This project aims to develop and demonstrate a novel CO₂ refrigeration technology based on hydraulic compression and expansion energy recovery. The project focuses on the development, characterisation, and experimental assessment of a liquid-piston-based compression and expansion system operating with CO₂ under subcritical and transcritical conditions.

The proposed technology combines quasi-isothermal compression with quasi-isentropic recovery of expansion energy, providing a fundamentally different approach to conventional vapour-compression systems. HYDROCOOL addresses the challenges associated with

the high operating pressures and limited flexibility of CO₂ refrigeration systems, while also targeting key limitations common to conventional cooling technologies, including insufficient coefficient of performance (COP), high lifecycle costs, reliability constraints, and limited operating temperature and pressure ranges.

The proposed approach is expected to substantially increase system efficiency, with the potential to nearly double the COP, while reducing mechanical stresses, extending equipment lifetime, and lowering operating and maintenance costs. The technology is particularly promising for applications with high and continuous cooling demand, including food storage, data centres, and air-conditioning systems. By enabling the use of CO₂ as a natural refrigerant while improving system performance, HYDROCOOL has the potential to significantly reduce the environmental impact of cooling technologies. Following the completion of the initial modelling and system design, the project has entered the pilot implementation and experimental validation phase. Current activities include the assembly and integration of the 17.6 kW pilot system, together with the preparation of experimental testing and the refinement of the project's environmental and techno-economic assessments.

LEMON – Large-Scale Magnetic Cooling

The LEMON project addresses a fundamental scalability limit in cryogenic cooling that constrains the entire global quantum technology sector, not only Europe. State-of-the-art dilution refrigeration relies on helium-3 and, while individual units can in principle be combined to increase output, doing so is highly inefficient and ultimately not scalable: helium-3 supply is severely limited and depends on a non-scalable supply chain, sourced almost exclusively from military-origin production concentrated outside the EU.

This constraint is not specific to Europe — even nations holding larger helium-3 reserves remain limited by the same underlying

supply and efficiency bottleneck. As a result, no current cooling technology can economically supply the several hundred microwatts to tens of milliwatts of cooling power that fault-tolerant, large-scale quantum computers will require. LEMON develops a continuous Adiabatic Demagnetization Refrigeration (cADR) process that is inherently modular: individual units can be connected in series or parallel to reach, in principle, arbitrarily high cooling capacities without relying on helium-3 at all. Led by kiutra GmbH (Munich, Germany), the project will design, build, and validate a demonstrator delivering 20 μ W of cooling power at 20 mK, directly benchmarked against incumbent dilution technology. By removing this cooling-power ceiling, LEMON aims to unlock the scale-up of quantum computing worldwide, while also eliminating Europe's dependence on a scarce, geopolitically concentrated resource.

MAGCCINE - Clean and Efficient Cooling in Vaccine Transportation Using Rotating Magnetocaloric Effect

The MAGCCINE project leverages magnetocaloric refrigeration to address the critical vulnerabilities of traditional vapor-compression systems in vaccine cold-chain logistics.

Failures in temperature control can lead to vaccine degradation and losses. Therefore, this challenge is particularly relevant for mobile, decentralised and resource-constrained cold-chain logistics, where compactness, reliability and environmental sustainability are essential.

Aimed towards portable applications, MAGCCINE replaces the conventional application of a variable magnetic field with the rotational magnetocaloric effect, exploiting the relative rotation of an anisotropic magnetocaloric material within a constant magnetic field. This radically new approach significantly reduces the required mass of permanent magnets, lowering system volume, weight, and production costs while optimizing energy efficiency and reliability, and

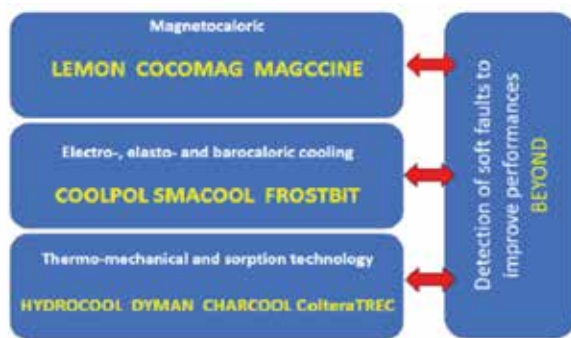


Figure 2: Structure of the thematic areas of the projects and potential collaborations.

simplifying system design.

To validate this clean and resilient cooling solution, the project combines the development of advanced anisotropic magnetocaloric materials; implementation of specialized bespoke characterisation techniques; comprehensive multiphysics modeling (materials, magnetic field, and fluid flow); heat-transfer optimisation; design optimization of magnetic field sources and functional prototype integration.

SMACool - Shape Memory Alloy based elastocaloric Cooling system

The project SMACool develops a functional air-conditioning device for residential buildings, based on the emerging technology of elastocalorics.

The interdisciplinary project consortium consisting of three European Universities from Germany, Italy and Slovenia and one emerging high-tech Company from Ireland, covers several project objectives, including the construction and validation of an application-specific elastocaloric cooling system device, the creation of a versatile validation environment for quantitative validation of future elastocaloric devices, the realization of a multi-physical numerical simulation platform for simulative assistance in elastocaloric device development, the development and characterization of elastocaloric-specific optimized materials, and the development of an efficient electric drive unit suited for the specific needs of elastocaloric system devices.

The resulting SMACool system is targeting an efficiency increase by a factor of up to two compared to state-of-the-art HVAC (Heat,

Ventilation, and Air-Conditioning) systems and will have high impact on potentially cutting down global energy consumption in the residential building sector and also other cold generation fields.

SECTION 3: PORTFOLIO SCOPE AND STRATEGIC ACTIVITIES

To reach further and go beyond the typical, individual project development, the EIC Clean and Efficient Cooling Portfolio pursues coordinated strategic activities designed to maximize its collective scientific, technological and societal impact. The portfolio brings together eleven EIC Pathfinder projects developing breakthrough cooling solutions with lower energy consumption, reduced environmental impact and limited dependence on CRMs.

The projects are organised in complementary thematic areas—magnetocaloric cooling; electro-, elasto- and barocaloric cooling; and thermo-mechanical and sorption technologies—together with a transversal axis on modelling, control, fault detection and maintenance. This structure enables cross-project exchange on common scientific and technological challenges despite differences in physical principles, targeted applications and operating temperatures, which range from cryogenic conditions to near-ambient cooling. Collaboration is structured through three working groups.

The Techno-Scientific Working Group promotes cooperation on shared experimental methods, heat-transfer phenomena, simulation tools, performance indicators, research infrastructure and possible technology hybridisation.

The Innovation, Regulation and Standardisation Working Group addresses market positioning, exploitation strategies, intellectual property, stakeholder engagement and common regulatory pathways, including compliance with the F-Gas phase-down and the Kigali Amendment. The Dissemination and Exploitation Working Group coordinates communication, networking, demonstrations and joint outreach. Figure 2 schematizes the main thematic area of each project and the potential interactions.

SECTION 4: HOW TO FOLLOW THE DEVELOPMENT OF THE PROJECTS

Progress across the portfolio can be followed on the joint portfolio website <https://eic-cooling.eu/>, which provides news and updates on portfolio-wide activities together with links to each individual project's own website.

Additional updates are shared through a portfolio newsletter, the individual projects' social media channels, and through joint communication and dissemination activities, such as the joint workshop at CLIMA 2025 (Milan) and participation in Thermag XI 2026 (Ljubljana). Interested readers are encouraged to consult the portfolio website for an overview and contact form, or to reach out to the corresponding Communication Managers directly for updates on specific thematic areas.

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Artificial Intelligence and the Labor Market



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***What will be the Impact of AI on the Labor Market?
Economists Have not yet Reached an Agreement***

ABSTRACT

This subject is present in the media in general and has taken up a good part of the technical publications, generating articles about the doubts that hover in the job market.

Will AI take my job?

As president of international relations at ABRAVA, I have participated in several international meetings, and the concern is the same around the world, but although everyone understands that this is a global issue, everyone agrees that the solution needs to be local. No one knows yet what the impact of AI will be on the labor market; economists have not yet reached an agreement, and they are still divided into at least three camps.

In this article, we will talk about a work published in April 2026 by the Carnegie Endowment for International Peace.

FUTURE OF WORK

a) The magnitude and direction of AI's impact on the future of work

The study, "Three Views on the Future of Work," published in April 2026 by the Carnegie Endowment for International Peace, mapped the three dominant currents among researchers and policymakers. The figure 1 of the published work demonstrates that perspectives on the impact of AI in the workplace vary in magnitude and direction. By mapping the three streams, the study graphically presented the distances between them and classified the most likely views of job disruption

caused by AI into three groups: Excited, Patient, and Alarmed.

b) Three visions on the future of work.

1. Enthusiastic, a group of those who argue that AI will create more opportunities than it eliminates.

2. Patients, those who argue that the replacement will be gradual and will occur over decades.

3. Alarmed are those who believe that AI will replace a large portion of office work in the next decade.

This is not a dispute between optimists and pessimists; each view bases its position on some facts, and the distance between them demonstrates how much uncertainty there is still on this subject

The enthusiasts insist that this movie has already been seen, that the great technological waves have destroyed categories of jobs and created others that no one imagined. The argument is not that the transition will not take place without sacrifices and adaptations, but that the result will be positive. They argue that new technologies have always reshaped work. About sixty percent of jobs in 2018 were in professions that did not exist in 1940, and there was no disruption in the labor market during that period. Enthusiasts believe that AI will generate such great economic growth that it will increase the demand for human labor in new areas, offsetting losses in automated categories. Let's believe that this is possible! **Patients** recognize the transformative potential of AI but disagree with the speed at which it will act because they believe that current technical limitations, coupled with practical barriers to adoption in enterprises, will slow the pace of replacement. The argument here is about the difference between what AI does well and what it can't do when it comes to complex tasks of the kind

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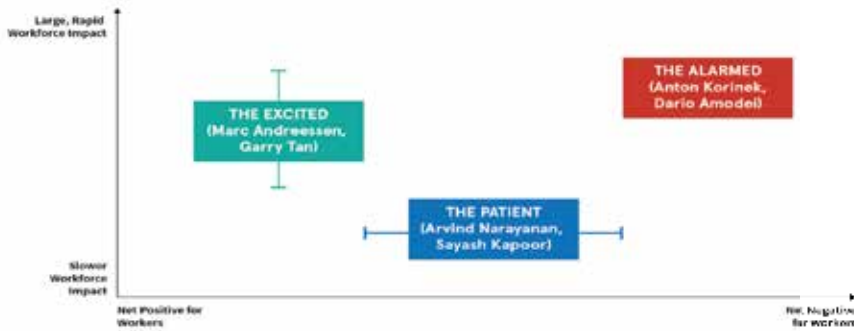


Figure 1: Perspectives on AI's Workforce Impact Vary by Magnitude and Direction.

TECHNOLOGICAL CYCLES Costantes and Rapid Transformations					
FIRST WAVE	SECOND WAVE	THIRD WAVE	FOURTH WAVE	FIFTH WAVE	SIXTH WAVE
Hydraulic Power	Power of Steam	Electricity	Petrochemicals	Digital Networks	IoT and AI Datacenters
Textiles	Railways	Chemicals	Electronics	Software & Robots	Drones
Iron	Steel	Internal Combustion Engine	Aviation	New Media	Clean Technology
60 YEARS	55 YEARS	50 YEARS	40 YEARS	35 YEARS	5 YEARS
1785	1845	1900	1950	1990	2020
					2025

Table 1: Technological Cycles.

that a human worker is capable of doing. According to them, there is a structural gap between what AI does well in standardized tasks and what it cannot do when the actual work requires interpretation of context, adaptability, relationship, etc.

These factors will influence the pace of implementation in companies that will have to overcome barriers such as regulation, implementation costs, etc. **The alarmed** believe that the replacement will be quick. They start from three premises:

1. Over the next decade or sooner, AI systems will be able to solve most office workers' tasks.
2. Employers will prefer to use AI and fire human workers.
3. New jobs will not be enough to compensate for those laid off by the automation made by AI leading to an increase in unemployment.

It is important to note that this group, of those alarmed, is not without its reasons about the exchange of humans for AI, because in the real labor market, we have seen that in mergers and acquisitions, layoffs or the slowdown in hiring affect

more workers with little practical experience and those in sectors considered easier to be replaced by AI, such as human resources, administration, law, accounting and IT. It remains to be seen how many new jobs have been or will be generated in new functions to compensate for these layoffs.

c) Consensus

Despite the disagreement between these three groups, there is at least a consensus among them; the debate is not yet fully resolved, and, therefore, it is necessary to act now. AI can reduce jobs, redesign them over time, create completely new ones, or do all three at once, but we need to act now, because the argument for starting to act doesn't depend on which scenario will happen. The labor market rarely moves in a straight line. He alternates between advance and waiting, short, medium, and long-term vision, conviction and doubt, trial and error, etc., always trying to find balance. Governments that wait for certainty before investing in data centers, requalification programs, and new

regulatory frameworks will be too late. This also applies to large corporations and our companies.

For Brazilian workers and companies, the risk is not only unemployment; there is also the risk of obsolescence of the function, the one in which the function continues to exist, but the professional who has not learned to work with AI, despite continuing with his job, may be worth less than those who have learned. Therefore, let's stay tuned and follow the evolution of this new era that is certainly here to stay.

TECHNOLOGICAL CYCLES

To delve a little deeper into the previous considerations about the impact of AI on the labor market, let's take a look at what has occurred in previous cycles of technological advances. The stages of evolution from the pre-industrial era to the present day can be divided at least into six stages, or "waves". The summary presented in Table 1 gives us an idea of the duration and the technological evolution that occurred in each stage. We can see that the duration of each wave has been becoming shorter. Each of them brought us extremely important points for the evolution of industry and society.

THE THIRD WAVE

Although the first and second waves were fundamental for the start of modernization, let's start by commenting on two points of the Third Wave:

a) Electricity:

Electricity is one of the greatest forces of transformation in our history. The mastery of this invisible force exceeded all expectations of the time. It went far beyond replacing candles with lamps in the windows of homes; It went to industries and powered engines that replaced human and animal physical strength with constant force, something unimaginable at the time. The assembly lines gained an uninterrupted rhythm, and the scale of manufacturing reached unprecedented levels. In addition to

the revolution in industry, electricity has shortened distances by giving life to telegraphs and telephony; communication that used to take weeks now happens in minutes or seconds. These advances led to others; hospital medicine moved from the old mercury thermometers to safe treatment environments, clean rooms, etc., equipped with continuous monitoring devices. The rhythm of social development accelerated, shaping the modern era that emerged quickly. In short, electricity was disruptive, and this did not bring any unemployment; on the contrary, it brought new jobs in areas that did not even exist.

b) Internal Combustion Engines:

The first internal combustion engine was invented by Nikolaus August Otto in Germany in the mid-nineteenth century to replace steam engines. Among other advantages, it was lighter, more efficient, and capable of producing more power than the steam engines of the time. Even after more than a century since this invention, they are part of many people's daily lives. From automobiles, generators, and large machines such as aircraft and ships, they continue to use this technology. But now, in the latest wave, combustion engine cars have begun to find a strong competitor, which is precisely the electric-powered vehicles.

THE FIFTH AND SIXTH WAVES

Returning to our topic on the impact of artificial intelligence on the labor market, the automotive industry is a good example of change.

a) Battery Electric Vehicle

What is happening before our eyes is one technological, industrial, and perhaps geopolitical disruption of rare proportions in modern history. The automotive cycle, shaped for more than a hundred years by mechanical engineering, is being displaced by a new productive logic. It's not just about switching from gasoline to electricity or battery. The change is more profound: the automobile of the 21st century is moving from being essentially a thermodynamic machine to becoming

a digital, electric, connected, and permanently upgradeable platform. The modern electric vehicle is not a conventional car retrofitted with a battery. It is, increasingly, a high-performance computer on wheels. The expression "software-defined vehicle" translates this turning point well. The car becomes an integrated platform of sensors, artificial intelligence, connectivity, entertainment, navigation, energy management, driving assistance, remote updating, and permanent interaction with the user and the surrounding infrastructure. The most interesting thing is that, even with all this paraphernalia, electric vehicles are more economical in operation and, probably, in maintenance.

Are we close to the end of the combustion engine cycle?

Maybe for automobiles, yes, but as mentioned above, they have other applications that will continue to require their application, whether for logistical needs, power, or for strategic reasons; time will tell us:

b) HVACR Market

What to think about our HVACR market?

The impact of electricity in the automotive area, where the automobile is being displaced by a new production logic, is also being observed in HVACR products and systems. This phenomenon started way back when pneumatic controls were replaced by electric ones, then by analog electronics, and quickly digital controls appeared. The famous DDC (Direct Digital Controls) with their microcontrollers that read data from sensors and make automatic decisions to control equipment in real time opened the doors to the Internet of Things (IoT), and from there, in a leap, the application of Artificial Intelligence is rapidly being applied to products and facilities. But at least for now, here in Brazil, both in the automotive industry and in the refrigeration and air conditioning industry, these real disruptions are not causing consistent job losses but have required professional qualification and even contributed to the lack of a skilled labor force. So, analyzing what happened in the past with electricity and now in these two sectors, we're on the middle way; that is, probably the Patients are right.



The Presidents of the 21st EU Conference in Milan

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- 2 Yosr Allouche, Director General International Institute of Refrigeration
- 3 Marco Buoni, Director Centro Studi Galileo
- 4 Said El Harch, Vice-President of U-3ARC
- 5 Paolo Buoni, Renewable Energy Institute
- 6 Enrico Buoni, Centro Studi Galileo
- 7 Russell Patten, Director General EPEE
- 8 Madi Sakandé, President of U-3ARC
- 9 Carloandrea Malvicino, enlarged Europe - CO₂ emission reduction strategies director Stellantis
- 10 Ina Colombo, Head of EU and International Programmes IIR
- 11 Steve Gill, Founder of World Refrigeration Day
- 12 Andrea Voigt, Board Member Cool Coalition

- 13 Bettina Schreck, International Expert HEAT
- 14 Bente Tranholm-Schwarz, Deputy Head of Unit DG Clima European Commission
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- 19 Tom Nickson Climate Campaigner At Environmental Investigation Agency - EIA
- 20 Andres Sepulveda, Incoming Vice-President and Member of ASHRAE
- 21 Armin Hafner, Professor at the NTNU
- 22 Lambert Kuijpers, Member TEAP–RTOC

The Kigali Amendment in Ibero-America: A Regional Commitment to Transform Refrigeration and Combat Climate Change



Bolivar Monroy

*Vice president,
IIAR-ACAIRE Colombia chapter,
Technical Director,
Asociación Colombiana de Acondicio-
namiento del Aire y de la Refrigeración
(ACAIRE)*

Cooling systems (air conditioning and refrigeration) and heat pump systems have become essential technologies for public health, food security, industrial development, and human well-being over the past decades.

In 2016, the Parties to the Montreal Protocol adopted the Kigali Amendment, an international agreement that establishes a schedule for the gradual phase-down of hydrofluorocarbons (HFCs) production and consumption, addressing this challenge through the adoption of low-global-warming-potential (low-GWP) refrigerants and more sustainable technologies.

Nearly a decade after its adoption, Ibero-America has emerged as one of the regions most committed to implementing this transition.

A REGION COMMITTED TO CLIMATE ACTION

Most Ibero-American countries have ratified or formally accepted the Kigali Amendment, incorporating its commitments into national policies on climate change, energy efficiency, and sustainable development.

Across Latin America and the Iberian Peninsula, virtually every country has made significant progress in this process, including:

- Argentina
- Bolivia
- Brazil
- Chile
- Colombia
- Costa Rica
- Cuba
- Ecuador
- El Salvador
- Spain
- Guatemala
- Honduras
- Mexico
- Nicaragua

- Panama
- Paraguay
- Peru
- Portugal
- Dominican Republic
- Uruguay
- Venezuela

Throughout the region, there is broad recognition of the strategic importance of the HVAC&R sector in achieving climate objectives while strengthening economic competitiveness.

The Kigali Amendment represents a profound technological transformation, driving the adoption of equipment that is more energy-efficient, safer, and environmentally sustainable.

Among the common regional priorities identified are:

- Transitioning to low-GWP refrigerants;
- Strengthening the training and certification of technicians and engineers;
- Updating technical standards, regulations, and safety codes;
- Improving refrigerant recovery, recycling, reclamation, and destruction systems;
- Promoting Minimum Energy Performance Standards (MEPS), supported by energy labeling programs; and
- Providing incentives for technological modernization.

Energy efficiency has therefore become an essential component of emissions reduction. Modern equipment not only uses refrigerants with a lower climate impact but also consumes significantly less energy throughout its operational lifetime.

THE ROLE OF NATURAL REFRIGERANTS AND EMERGING ALTERNATIVES

One of the Kigali Amendment's



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most significant impacts has been accelerating the adoption of technologies using environmentally friendly refrigerants.

Across Latin America, the solutions gaining the greatest market share in commercial and industrial applications include:

- **Carbon dioxide (CO₂, R-744):** Widely used in supermarkets, retail stores, and convenience stores.
- **and industrial solutions**, as well as in certain secondary refrigerant applications.
- **Isobutane (R-600a):** Extensively used in domestic refrigerators as a direct replacement for R-134a.
- **Ammonia (R-717):** A highly energy-efficient and cost-effective solution for large-scale industrial refrigeration systems.
- **Water (R-718):** In several countries, district cooling and district energy systems use water as a refrigerant medium, reducing the need for individual cooling systems while providing additional environmental and operational benefits.

At the same time, many manufacturers and suppliers serving the region have incorporated transitional synthetic refrigerants into their product portfolios, including R-32, R-454B, R-455A, and R-454C. These refrigerants facilitate a gradual transition toward lower-GWP solutions while maintaining high levels of energy performance and significantly reducing the sector's climate impact.

CHALLENGES STILL FACING THE REGION

Although substantial progress has been achieved, significant challenges remain before the transition can be fully consolidated.

Key challenges include:

- Replacing an installed base of equipment that is more than ten years old;
- Expanding the availability of technicians qualified to work with emerging technologies;
- Improving access to financing for small and medium-sized enterprises (SMEs);
- Continuously updating technical

regulations, standards, and safety requirements;

- Strengthening infrastructure for refrigerant recovery, reclamation, recycling, and destruction; and
- Raising awareness among end users and facility owners about the economic and environmental benefits of upgrading to modern equipment using low-impact refrigerants.

AN OPPORTUNITY TO TRANSFORM THE HVAC&R SECTOR

The Kigali Amendment represents a unique opportunity to modernize the HVAC&R sector throughout Ibero-America.

Beyond its contribution to climate change mitigation, the gradual phase-down of HFCs is driving technological innovation, improving energy efficiency, reducing operating costs, and enhancing the competitiveness of businesses across the region.

Technical associations and industry organizations play a fundamental role in promoting knowledge transfer,

developing skilled professionals, and encouraging the adoption of industry's best practices.

Regional cooperation will be decisive in accelerating the implementation of sustainable solutions and building a more efficient, resilient HVAC&R market aligned with international climate goals.

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The new EU-funded project IMPACT-F, or the Integrated Mitigation Platform for Assessing Climate Targets for F-Gases, aims to help governments develop more effective cooling and climate policies by providing access to advanced modelling tools. In many countries, limited data availability and modelling capability create significant challenges for evidence-based policy development and decision-making.

India's Data Centre Landscape Status, Challenges, and Opportunities



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ISHRAE Position Document

INTRODUCTION

India is rapidly transforming into a global digital infrastructure powerhouse. The convergence of cloud adoption, Artificial Intelligence (AI) emerging across all businesses and services, the telecom sector's transition from 4G to 5G, the Digital Personal Data Protection (DPDP) Act and its data localization requirements, the growth of digital public infrastructure, expansion of fintech, Industry 4.0, and other forces are driving unprecedented growth in Data Centers (DCs). Unlike previous growth cycles dominated by storage and cloud computing, the next decade will be defined by AI factories and High-Performance Computing (HPC), fundamentally altering the thermal and energy profile of DCs. Today, DCs have evolved from being IT assets into energy-intensive industrial infrastructure, where cooling systems have become mission-critical.

The HVAC&R fraternity is no longer a supporting stakeholder, but a strong strategic enabler responsible for ensuring the efficiency, sustainability, reliability, and resilience (R&R) that are a key focus for all DCs. The load profile and load density of IT equipment in DCs has undergone a radical shift.

Going forward, the industry's success will increasingly depend on how effectively it manages four resources simultaneously: Power, Cooling, Water, and Carbon.

ISHRAE (Indian Society of Heating, Refrigerating and Air-Conditioning Engineers) envisioned the growth of data centers many years ago, and has been working continuously to empower the DC community in a holistic manner by

offering sustainable, reliable, and highly effective cooling solutions. ISHRAE has formed a Technical Group (TG: H-104 – Data Centre) under the ISHRAE Technical Committee (ITC). This diverse group comprises industry experts, academia, OEMs, designers, and leading consultants.

INDIA'S DATA CENTER LANDSCAPE

India has emerged as one of the fastest-growing DC markets globally, led by Mumbai, Chennai, Hyderabad, Bengaluru, Pune, and Delhi/NCR. Hyperscalers, colocation/enterprise operators, edge data centres, and AI infrastructure providers are aggressively expanding capacity. In 2016 (a decade ago), India had only a few MW of IT capacity; today, designed IT capacity stands at 1.5-1.6 GW, and is projected to cross 8 GW or more by 2030. Figure 1 illustrates the projected growth in IT capacity starting from 2025 until 2028.

The Indian DC market is simultaneously experiencing three structural shifts, supported by a city-wise distribution of capacity as shown in Figure 2.

AI-Driven Densification

Traditional enterprise workloads operated at 3–8 kW/rack, while hyperscale facilities typically range between 10–20 kW/rack. AI clusters are now pushing rack densities toward 30–80 kW/rack or even more, with some GPU deployments exceeding 100 kW/rack. This fundamentally challenges conventional air-cooling architectures.

Energy as a Key Resource

Power consumption has become primary constraint, rather than land

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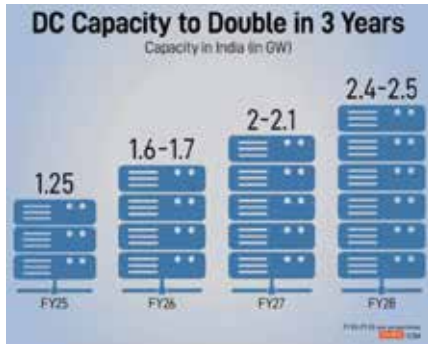


Figure 1: India's Data Center IT Capacity Growth, FY25-FY28.



Figure 3: Direct Liquid-Cooled Hardware in a Modern Data Centre.

availability. Large campuses now require 100–500 MW of dedicated power, transforming DCs into major industrial electricity consumers. Central and state Governments have made grid capacity a key focus area in recent years. The DC market presents a major opportunity for India to attract investment and strengthen the economy.

Energy will remain a critical constraint going forward, and new cooling solutions will be essential to reduce consumption significantly.

Sustainability as a Business Imperative

National and International end-users and operators increasingly demand low-carbon infrastructure. Consequently, operators are actively pursuing a Power Usage Effectiveness (PUE) below 1.3, a significant reduction in Water Usage Effectiveness (WUE) though today's DCs are not operated by water cooled chiller unfortunately owing to several reasons and challenges, and an increase in the share of renewable energy to as much as 50–80% of total energy use. Some DC operators have already set target to become carbon neutral by 2035/2040/2045. Consequently, HVAC&R decisions

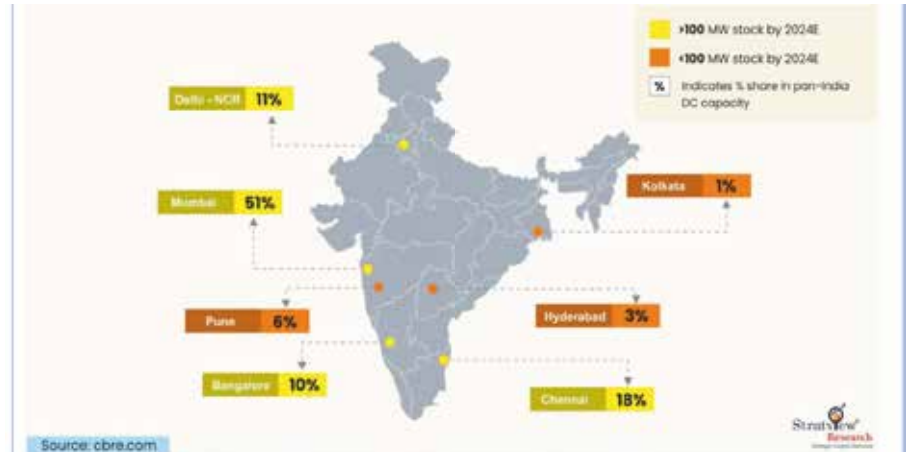


Figure 2: City-Wise Share of Data Centre Capacity in India.

Chilled Water Supply Temp.	Cooling Performance (kW/TR)
7°C	0.50 – 0.60
12°C	0.42 – 0.50
16°C	0.35 – 0.42
20°C	0.28 – 0.35

Table 1. Indicative Cooling Performance (kW/TR) at Varying Chilled Water Supply Temperatures.

now directly influence Green Data Centre Certifications, ESG performance, operating expenditure, and investment attractiveness. New and emerging cooling technologies are becoming the new norm across all categories of data centres – colocation, enterprise, edge, and hyperscale.

COOLING STATUS IN INDIAN DATA CENTRES

Data Centres require robust cooling to process loads through servers, CPUs, and GPUs, which generate significant heat. Inadequate cooling reduces the performance, reliability, and life of IT equipment; hence cooling can never be compromised in DCs. Traditional air-cooling (CRAC/CRAH, hot-aisle/cold-aisle design) remains common for conventional IT loads; however, it is reaching its limits with modern IT equipment running very high-density AI workloads. Recent advancements include Direct-to-Chip Liquid Cooling (DCLC) and Liquid Immersion Cooling (LIC), which remove heat much more efficiently and support high-density AI workloads. The industry is increasingly adopting hybrid air-plus-liquid

cooling systems, with liquid cooling becoming essential for next-generation AI and HPC DCs due to its higher efficiency and lower energy consumption. India today has 1.5 GW of IT load, which translates into 0.75 million TR of cooling demand. With IT load expected to grow to 8 GW by 2030, cooling demand will rise sharply, and integrated cooling systems will become the new norm for AI workloads. Advanced cooling systems will be more efficient; however the share/magnitude of cooling required will be extraordinarily high. It is therefore important to factor in the carbon footprint of cooling infrastructure while planning to meet sustainability goals. Supplying chilled water at higher temperatures has now become the baseline across the industry.

Under this approach cooling performance (kW/TR) can reach as low as 0.28–0.35 kW/TR for a chilled water supply temperature of 20°C, as summarized below.

CHALLENGES IN INDIAN DATA CENTRES

While the DC sector which does not yet have formal industry status, the Installation of Data Centres in

Challenge	Description
Thermal Management of AI Workloads	AI has become the single largest engineering challenge for DC designers. Traditional Computer-Room-Air-Conditioning (CRAC) and Computer-Room-Air-Handler (CRAH) systems encounter limitations beyond 20-30 kW/rack due to: • Increased fan energy consumption • Airflow recirculation and hotspot formation • Reduced cooling effectiveness • Higher pressure-drop requirements The industry is transitioning from air as the primary heat-transfer medium toward liquid-based thermal management. India needs to build greater capacity to manage this transition.
Power Availability and Grid Constraints	Power availability has become the biggest bottleneck in hyperscale expansion. Challenges include: • Long utility connection timelines • Transmission infrastructure limitations, and location of Green Power Sub-Stations • Peak summer grid stress • High electricity tariffs DCs are shifting from being power consumers toward becoming “power ecosystem participants,” requiring integration with renewable energy (RE), Battery Energy Storage Systems (BESS), and grid-interactive operations. Small Modular Reactors (SMRs) could emerge as a new baseline power source.
Water Sustainability	India is a water-stressed nation, making water-intensive cooling solutions increasingly unsustainable. Conventional cooling towers pose challenges such as: • High water consumption • Evaporative losses • Water treatment requirements • Blowdown disposal Water availability may eventually become a site-selection criterion equivalent to power availability. Future facilities should prioritize closed-loop cooling systems, water reuse and recycling, alternative heat-rejection technologies, and water-positive campus strategies.
Refrigerant Transition and Environmental Regulations	The HVAC&R industry is simultaneously navigating refrigerant transitions driven by Kigali Amendment obligations. Key challenges include: • Migration from high-GWP refrigerants • Adoption of low-GWP alternatives • Flammability management (A2L refrigerants) • Workforce training and safety compliance Future-proofing refrigerant choices has become essential to avoid stranded assets over 20-30 year facility lifecycles.
Talent and Skill Gap	Data center engineering requires multidisciplinary expertise spanning mechanical & electrical engineering, thermal sciences, power systems, controls engineering, sustainability, and digital technologies. India currently faces shortages in specialized competencies related to: • Cooling Technologies (DCLC, LIC etc.) • Use of CFD modelling in air-flow optimization, UHI Mitigation, etc. • AI workload planning • Digital twin deployment • Energy optimization The industry has already taken initiatives, including those by CII (DCAP for skill development, capacity building, certification, and accreditation of Data Center Professionals) and Telecom Sector Skill Councils such as TSSC.

Table 2: Emerging Challenges in Indian Data Centres.

India is growing rapidly, and several challenges must be addressed to harness this growth and help India in becoming a global Data Centre hub. Refer to Table 3 for a comprehensive list of the major challenges.

OPPORTUNITIES FOR THE HVAC&R FRATERNITY

The evolving data center ecosystem presents a significant opportunity for HVAC&R professionals, summarized across six focus areas in Table 3. Two cooling technologies stand

out as especially relevant to the opportunities above: rear-door heat exchangers, which extend the life of air-cooled architectures, and immersion cooling, which is fast emerging as the platform of choice for the highest-density AI racks.

CONCLUSION AND WAY FORWARD

India's Data Centre growth story is no longer just an IT story; it is fundamentally an energy, cooling, and sustainability story. The future competitiveness of

Indian data centres will depend on successfully balancing performance across power, cooling, water, and carbon.

The HVAC&R fraternity must evolve from an equipment-centric mindset to becoming infrastructure strategists responsible for lifecycle performance optimization.

The way forward requires coordinated action in five priority areas:

- 1) Accelerate adoption of liquid cooling technologies for AI infrastructure.
- 2) Follow National benchmarks for

Opportunity Area	Key Focus Areas
Air Cooling Optimization	• Indirect evaporative cooling • Rear-door heat exchangers • Containment systems • Adiabatic cooling
Liquid Cooling Technologies	• Direct-to-chip liquid cooling (DCLC) • Liquid Immersion cooling (LIC) • Hybrid cooling systems Liquid cooling may become mainstream for AI workloads above 50 kW/rack.
Digital Engineering and Smart Operations	Digitalization presents immense opportunities through: • Digital twins • AI-based controls • Predictive maintenance and IoT-enabled sensing • Continuous commissioning (Cx) Real-time optimization can significantly reduce energy consumption without compromising uptime. Several companies have already developed AI-based tools to optimize DC operations.
Energy Efficiency Leadership	HVAC&R professionals can become energy strategists by optimizing: • Chiller plant performance and partial-load efficiency • Heat recovery systems and thermal energy storage • Dynamic setpoint optimization Every 0.1 improvement in PUE translates into substantial energy and carbon savings over the facility's life.
Renewable Energy Integration	Future DCs will increasingly operate as integrated energy ecosystems comprising: • Solar photovoltaic (SPV) systems • Wind power procurement and hybrid systems • Battery energy storage systems • Green open-access arrangements • Microgrids
Water-Positive Infrastructure	• Hybrid cooling systems • Air-assisted liquid cooling • Wastewater utilization • Zero liquid discharge systems Water-neutral Green Campus designs that meets and exceed sustainability goals.

Table 3: HVAC&R Strategies.

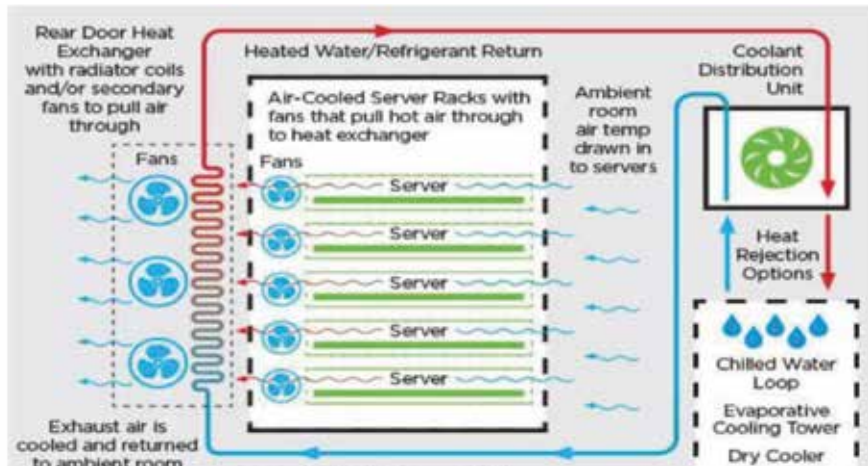


Figure 4: Rear-Door Heat Exchanger Cooling Schematic.



Figure 5: High-Density Liquid-Cooled Server Rack Infrastructure.

PUE WUE, and carbon intensity, as practised in the industry through various sustainability initiatives.

3) Integrate renewable energy, battery energy storage, and smart grids for Green Data Centres.

4) Develop a National DCcooling competency framework to address skill shortages.

5) Prioritize low-GWP refrigerants and sustainable thermal management practices.

India has a unique opportunity to build the world's most sustainable next-generation DC ecosystem. The HVAC&R fraternity will play a decisive role in determining whether this growth becomes energy-intensive or energy-intelligent.

This position document presents the collective perspective of the ISHRAE Technical Group on Data Centres (TG: H-104), constituted under the ISHRAE Technical Committee (ITC). It is intended to inform industry stakeholders, policymakers, designers, and built-environment professionals on the evolving Data Centre (DC) landscape in India.

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Our values come before all our innovations and milestones, and before every refrigerated cabinet we develop. Vision, inspiration, change and service are our starting point and our direction. Since 1963, they have been the compass guiding our journey worldwide. Our values determine all our choices, inspire all our ideas.

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the current TOP OF THE RANGE with 72 m³

**CD600 – CO₂ compressors,
the largest with 6 cylinders, 19 models,
displacement volume 39.85 - 99 m³/h**

The **new CD600** range offers a truly **advantageous solution** for **large industrial applications**, where in the past the only alternative was to use a large number of smaller compressors. It is an available and safer **alternative** to ammonia and an **excellent response** for a more **sustainable future to protect our planet**.

Range Technical Characteristics:

- Extended application envelope
- Best fit for heat pump design
- The largest range of compressors for industrial systems
- Patented oil containment design for lowest oil entrainment ratio
- Inverter drive capability
- High COP levels



WE WILL BE PRESENT AT THE FOLLOWING EVENTS

XXXI IAR INTERNATIONAL SEMINAR 2026
LEÓN, GUANAJUATO (MX) / 7.-9. OCTOBER

CHILLVENTA 2026 HALL 5 / BOOTH 5-216
NUREMBERG (DE) / 13.-15. OCTOBER

RETA NATIONAL CONFERENCE 2026
ORLANDO, FL (USA) / 26.-30. OCTOBER

HVACR VIETNAM 2026
SECC, HO CHI MINH CITY (VN) / 4.-6. NOVEMBER

XXXII SEMINARIO INTERNACIONAL IAR 2026
LONDRINA, PR (BR) / 11.-12. NOVEMBER

DKV DEUTSCHE KÄLTE-UND KLIMATAGUNG 2026
INGOLSTADT (DE) / 18.-20. NOVEMBER

SIFA 2026
LYON (FR) / 24.-26. NOVEMBER



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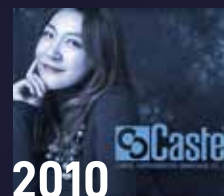
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Speakers and **Presidents** invited include Leading Global Experts from:
United Nations Environment (UNEP) | UN Industrial Development Organisation (UNIDO)
European Commission DG Clima | International Institute of Refrigeration (IIR-IIF)
European RAC Associations (AREA) | Association Française du Froid (AFF)
AHRI - ASERCOM - ASHRAE - EPEE | Politecnico di Milano, Torino
Universities of Ancona, Genova, Padova | The George Washington University (USA)
Heriot-Watt University, Glasgow Caledonian University, Imperial College of London,
Edinburgh Napier University, University of East London, The University of London |
Universities of Palermo, Perugia, Roma, and all the AC&R European Associations

