Carbon Containment Lab

Beyond Refrigerants: Alternative Cooling Technologies

Issue Brief for the 47th Open-Ended Working Group of the Montreal Protocol and Side-Event

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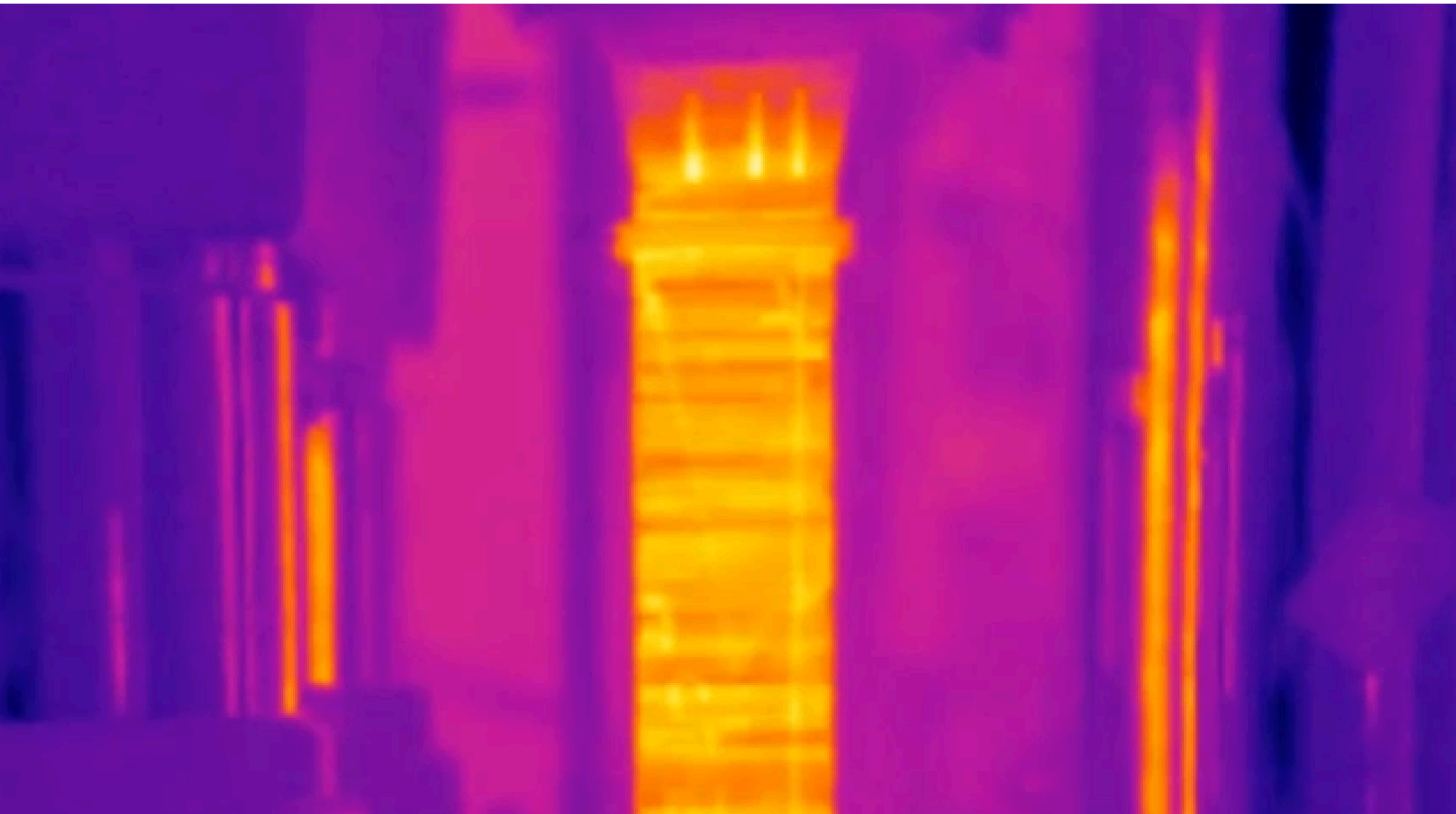

1. EXECUTIVE SUMMARY

- *What Are ACTs:* Alternative Cooling Technologies (ACTs) are cooling methods that do not use traditional refrigerants or vapor-compression systems. These include solid-state, passive, and hybrid systems.

- *Compliance Benefits:* ACTs can support compliance with HFC phasedown targets, especially in sectors with servicing challenges or where existing substitutes are not practical. The further development and broader deployment of ACTs expands the range of tools available to Parties in complying with the Kigali Amendment.

- *Climate Performance:* ACTs help meet the goals of the Kigali Amendment by avoiding the use of high-global-warming-potential (high-GWP) refrigerants and reducing energy use, lowering both direct and indirect greenhouse gas emissions.

- *Innovation Leadership:* The Montreal Protocol community can cultivate innovation by raising awareness of the role ACTs play in Kigali implementation. This includes encouraging early-stage research, capturing insights from pilot projects, and adapting assessment processes to recognize promising approaches even before full peer-reviewed validation. Openness to innovation has been central to the Protocol's past success and should continue with ACTs.

- *Multilateral Action:* As described in this Issue Brief[1], the Montreal Protocol can do more to maximize the potential of ACTs in facilitating Kigali implementation, increasing awareness of and access to a broader scope of substitutes and alternatives to high-GWP HFCs.

1. INTRODUCTION

The global transition away from high-global-warming-potential (high-GWP) hydrofluorocarbons (HFCs), as mandated by the Kigali Amendment to the Montreal Protocol, is well underway. Yet achieving long-term climate and compliance goals will require a rapid expansion in alternatives to high-GWP refrigerants in conventional vapor compression systems—especially given increases in heat waves and other extreme weather events. This will require a broader portfolio of approaches. Alternative Cooling Technologies (ACTs) present one such opportunity—offering fundamentally different ways to deliver cooling and protect the climate.

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[1] Cover image credit: Exergyn. 2025. Solid-State SMA Technology. https://www.exergyn.com/technology/.

ACTs include systems and methods that do not rely on vapor compression or fluorinated refrigerants. They encompass both active technologies—such as solid-state cooling, magnetocaloric and elastocaloric systems—and passive approaches including improved insulation, radiative cooling, and thermal mass strategies in buildings.

ACTs can complement the adoption of natural refrigerants and mid- to low-GWP chemical substitutes, expanding the portfolio of solutions available for a low-carbon cooling transition. Alongside ACTs, Lifecycle Refrigerant Management (LRM)—which aims to recover, contain, and properly dispose of existing refrigerant banks—remains essential to reducing current and legacy emissions. When working in tandem ACTs and LRM, along with natural refrigerants, can help ensure the phase down of HFC production and consumption under the Kigali Amendment and, potentially, enable Parties to go beyond compliance by transforming how cooling is delivered and sustained.

This Issue Brief highlights the importance of ACTs in supporting the objectives of the Kigali Amendment and in delivering additional climate benefits. It reviews progress and discussions from recent Montreal Protocol meetings, defines ACTs within the broader technological landscape, and outlines key early-stage technologies with potential relevance across markets and applications. It also acknowledges the proprietary and early-stage nature of the development of many ACTs, and the reluctance or inability of ACT developers to seek peer review or independent validation due to risks to intellectual property and startup business models.

The Issue Brief identifies specific areas where ACT development could be accelerated, including through more interaction with the Technology and Economic Assessment Panel (TEAP), potential pilot project funding under the Multilateral Fund for qualified ACTs, and integration into national cooling action plans.

By expanding focus to include ACTs, Parties to the Montreal Protocol can strengthen climate outcomes, promote innovation, and secure additional pathways to achieve Kigali Amendment goals.

2. DEFINING ACTs

a. Scope and Characteristics

ACTs are defined by their departure from conventional vapor compression systems and their avoidance or minimization of conventional refrigerants. These systems do not rely on the thermodynamic cycles that dominate traditional air conditioning and refrigeration, nor do they depend on high-GWP substances regulated under the Kigali Amendment.

By design, ACTs provide sustainable alternatives to cooling, and in so doing reduce or eliminate direct emissions associated with refrigerant leakage. ACTs therefore support the diversification of mitigation options in the cooling sector.

b. Categories of ACTs

ACTs fall into three general categories based on their operational principles:

1. **Active cooling technologies** use electrically or mechanically driven processes involving advanced solid-state materials. These include:
    a. *Elastocaloric systems*, which generate cooling through the stress-induced phase transition of shape memory alloys (SMAs).
    b. *Barocaloric systems*, which exploit pressure-induced thermal changes in solid-state compounds.
    c. *Magnetocaloric systems*, which utilize magnetic field-induced entropy changes in specialized materials.
    d. *Thermoelectric systems*, based on the Peltier effect, where electric current creates a temperature gradient across semiconductor junctions.
    e. *Thermoacoustic systems*, which use sound waves in gas-filled chambers to generate temperature gradients without moving parts or refrigerants.
    f. *Air-based systems*, which use air (R-729) as the working fluid in a reverse-Brayton cycle, providing refrigerant-free cooling through compression and expansion in a closed loop.
2. **Passive cooling technologies** function without external power input, relying instead on environmental conditions and material properties. This category includes:
    a. *Radiative cooling*, which emits infrared radiation to the sky to dissipate heat.

b. *Advanced building design*, such as shading, ventilation, orientation, and improved insulation that reduce cooling demand through architectural interventions.

c. *Two-phase cooling systems,* which transfer heat through evaporation and condensation of a working fluid in sealed channels, using passive capillary action without pumps or moving parts.

3. **Hybrid cooling systems** combine active and passive methods to enhance efficiency or broaden application potential. These systems integrate multiple cooling mechanisms to leverage both engineered and environmental advantages.

a. *Phase-change material (PCM) systems*, which store and release thermal energy through melting and solidification cycles, enabling load shifting and passive discharge of cooling over time.

b. *Desiccant-based systems*, which use hygroscopic materials to remove moisture from the air, reducing latent heat load before mechanical cooling and enabling hybrid operation with evaporative or solid-state technologies.

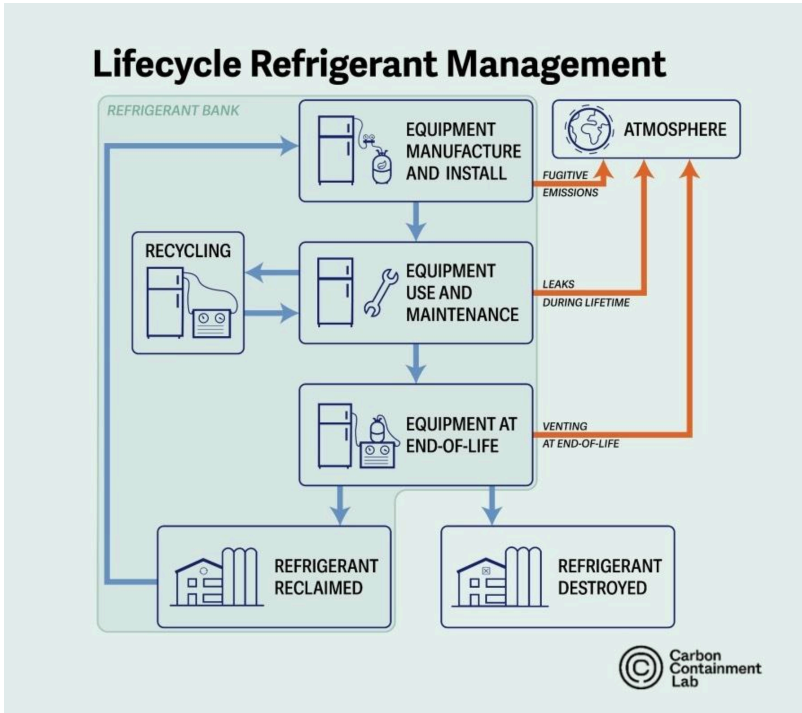
c. Ocean Water, Lake, and Groundwater Cooling Concepts, which use hydronic district cooling systems extract stable-temperature water from lakes or oceans to supply chilled water to buildings.

c. How do ACTs relate to Natural Refrigerants?

Natural refrigerants—including carbon dioxide (CO_2), ammonia (NH_3), and hydrocarbons—play an essential role in reducing GWP in traditional systems and are increasingly integrated into regulatory and commercial pathways. However, they are not the focus of this brief, as they still rely on vapor compression gas-based systems. Their deployment is already addressed through established channels such as sector-specific standards, safety codes, and existing market transformation initiatives.

d. How do ACTs relate to Lifecycle Refrigerant Management (LRM)?

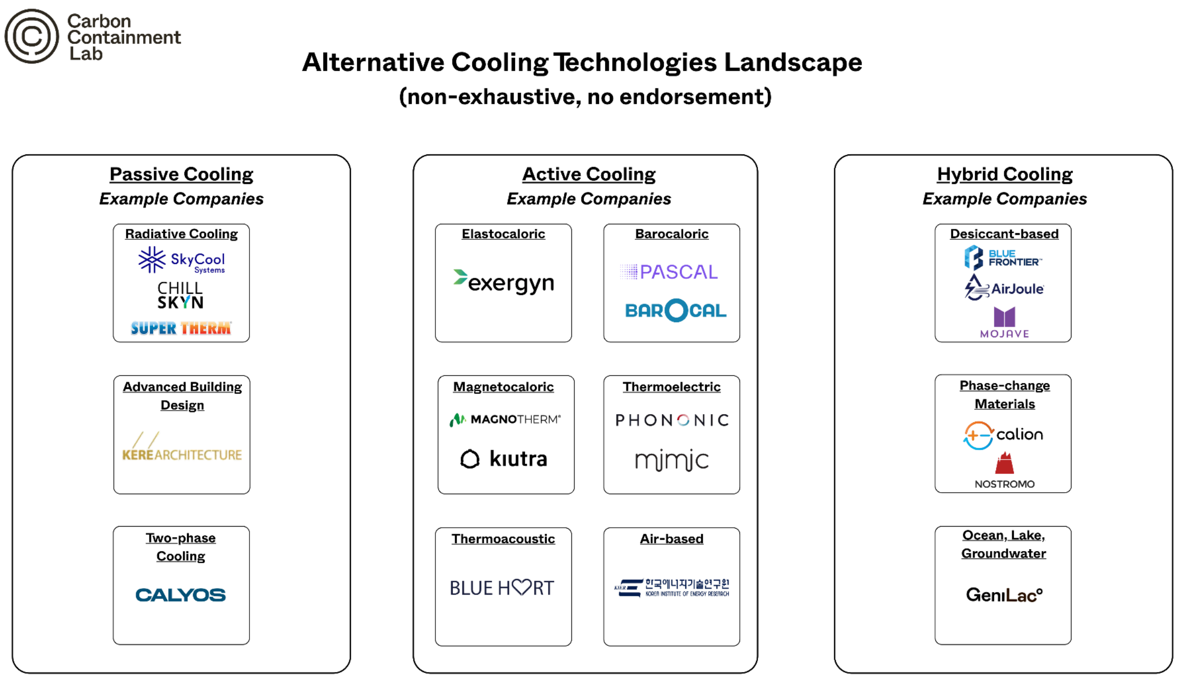
Lifecycle Refrigerant Management (LRM) is a comprehensive approach to minimizing refrigerant emissions by preventing leaks, recovering refrigerants during servicing and at end-of-life, and ensuring their reuse or destruction through environmentally sound practices. This is essential to maximizing the climate benefits of the HFC transition.



While ACTs reduce future dependence on refrigerants by offering non-gas cooling solutions, LRM ensures responsible management of legacy systems. Together, ACTs and LRM, along with natural refrigerants, support compliance with the Kigali Amendment and, potentially, enable Parties to exceed their obligations through deeper, system-level decarbonization.

3. EXAMPLES OF EMERGING ACTs

The graphic below visualizes key categories of ACTs currently in development or demonstration, along with a non-exhaustive list of representative companies. Inclusion is for illustrative purposes only and does not imply endorsement. These technologies differ in mechanism, application, and maturity but share the goal of providing sustainable, refrigerant-free, or refrigerant-minimizing cooling solutions.



4. CURRENT STATUS AND CHALLENGES OF ACTs

a. Technology Readiness

Many ACTs remain in the early to mid stages of development, with Technology Readiness Levels (TRLs) ranging from laboratory demonstration (TRL 3–4) to operational deployment (TRL 8–9). Solid-state systems such as ionocaloric and barocaloric cooling are currently undergoing bench-scale validation, while others, including thermoelectric and lake water cooling systems, are already commercially deployed. The variation in TRLs underscores the need for differentiated policy support tailored to each technology pathway's maturity level.

b. Validation and Proprietary Barriers

While several ACTs have demonstrated promising performance in controlled settings, the lack of peer-reviewed validation remains a constraint. Many developers maintain proprietary control over performance data to protect intellectual property and attract investment, limiting access to third-party evaluation. Protecting intellectual property is widely understood to be fundamental to achieving commercial scale, but obviously presents a challenge for public institutions and international bodies tasked with assessing climate and efficiency outcomes across emerging cooling technologies.

The Montreal Protocol's TEAP relies on published, peer-reviewed literature and independent third-party validation to assess technologies for inclusion in its reports. While this ensures technical credibility and consistency, it excludes many ACTs still under commercial development, where data is often proprietary or as yet unpublished.

To maintain the Protocol's responsiveness to innovation, TEAP may consider identifying promising approaches without issuing formal evaluations, endorsements, or other definitive commentary, thereby preserving openness to novel solutions while upholding methodological rigor. The objective is to increase the knowledge of Parties and other stakeholders to promising potential technology advances central to Kigali implementation and broader climate mitigation goals that might otherwise go unnoticed.

c. Infrastructure and Market Barriers

ACT deployment is constrained by the absence of enabling infrastructure, particularly in developing countries. Some ACTs require new material supply chains, specialized installation and maintenance skills, or integration with existing building systems.

Certification schemes, performance labels, and technology-neutral incentive programs are also largely lacking for ACT categories. These challenges are magnified in regions with low technical capacity or limited capital for energy system upgrades, where even minor infrastructure changes may be cost-prohibitive without external support.

Limited awareness of ACTs explains many of these barriers, and, as discussed above, greater knowledge can catalyze action among governments and in the private sector to help overcome these barriers.

d. Opportunities for Pilot Programs and Financing

Pilot programs and concessional financing can play a key role in advancing ACTs from demonstration to commercial deployment. The Multilateral Fund (MLF) for the Implementation of the Montreal Protocol can support pilot projects that test market-ready ACTs in diverse operational environments, especially those relevant to Article 5 Parties.

Bilateral projects may also serve as a platform for collaborative development, data generation, and technical training. Structured pilots that emphasize measurement, reporting, and verification (MRV) can help build the evidence base needed to scale ACT adoption.

Of course, assessing ACTs from a life cycle perspective remains difficult due to the wide variation in technology type, application, and maturity. Most technologies lack comprehensive environmental impact assessments, particularly those that include operational (use-phase) and end-of-life performance. This is further complicated by the low TRLs of many ACTs, which limit the availability of real-world performance and disposal data.

Cost also remains a major uncertainty across ACT types, with limited data available for system-level comparisons to incumbent technologies. It is not yet clear how upfront capital, maintenance, and lifecycle costs will scale, nor how they differ across active, passive, and hybrid systems. For passive and design-integrated solutions in particular, determining who bears the costs (i.e., developers, owners, or occupants) will be critical to evaluating feasibility and driving adoption.

However, as an ACT approaches market readiness, understanding its benefits and impacts via a comprehensive LCA is essential, as is determining whether cost will prove to be a barrier to broader adoption.

5. INCORPORATING EMERGING ACTS INTO THE MONTREAL PROTOCOL

ACTs offer promising pathways to support the goals of the Kigali Amendment by reducing dependence on high-GWP refrigerants and improving energy efficiency. While not drop-in replacements, ACTs expand the technical and policy options available to Parties and may warrant focused attention within the Montreal Protocol framework.

The following elements represent possible avenues for advancing ACTs, consistent with established practices under the Protocol:

a. Enhance ACT Expertise within TEAP and RTOC

As ACTs involve non-vapor compression technologies, exotic materials, and other innovations, Parties may consider strengthening ACT-specific expertise within the TEAP and the Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC).

Given the proprietary nature and early-stage development of many ACTs, where, as discussed above, early- to mid-stage startups are unable to publish core aspects of their technology without substantial risk of surrendering their intellectual property and forfeiting their investment case, theTEAP might consider developing a reporting track that identifies emerging approaches for informational purposes only—without making or implying endorsement.

These actions would allow TEAP to capture ACT developments that are not yet supported by peer-reviewed data or third-party validation, while maintaining its current evidentiary standards. It will also encourage the eventual validation via independent third-party assessment and lifecycle analysis for those ACTs nearing commercialization and market entry.

b. Support ACT Pilots through the Multilateral Fund

The MLF has an essential role to play in accelerating ACT deployment in Article 5 countries. Funding decisions could include pilot demonstrations of scalable and regionally adaptable technologies. Pilots could be structured to generate operational data, support workforce training, and evaluate integration with existing systems. Particular focus should be placed on ACTs that can verifiably reduce both direct and indirect emissions, and those applicable to underserved climatic zones or grid-constrained regions.

c. Foster Innovation through Transparency

To support proprietary development, Parties should consider establishing mechanisms that encourage the voluntary sharing of non-commercially sensitive ACT information. This could include anonymized performance data, case studies, and lessons learned from field deployment. Transparency can accelerate replication and inform public policy design without undermining private sector investment or intellectual property rights.

d. Policy Frameworks to Encourage Adoption

Finally, ACTs should be integrated into national cooling action plans (NCAPs), where appropriate, alongside refrigerant transition measures. NCAPs are country-led strategies supported by UNEP and other partners that aim to reduce cooling-related emissions, improve energy efficiency, and ensure sustainable access to cooling.

As countries develop and update these plans, governments may consider establishing ACT-specific procurement guidelines, revising building codes to allow for non-vapor compression systems, and embedding ACTs in financial incentive programs and/or for their own operations via purchasing policy. These steps will help ensure that ACTs are not excluded by legacy regulatory structures and can compete fairly in technology-neutral mitigation strategies.

These approaches are consistent with how the Montreal Protocol has previously supported innovation intended to facilitate the HFC transition under the Kigali Amendment, including in particular Decision XXXV/11 on Life-cycle Refrigerant Management at the Thirty-Fifth Meeting of the Parties (MOP 35) in Nairobi, Kenya, in 2023.

6. IMPORTANCE OF ACTs FOR CLIMATE, COMPLIANCE, AND INNOVATION

As Parties consider how ACTs might support implementation of the Kigali Amendment, it is useful to understand what outcomes they may enable—including climate benefits, compliance support, and broader innovation.

a. Montreal Protocol's Legacy of Supporting Innovation

The Kigali Amendment commits Parties to phasing down the production and consumption of HFCs by more than 80% by 2045 for Article 5 countries. Discussions at recent OEWG and MOP sessions have underscored the need to explore additional pathways to meet these goals. ACTs, though not drop-in substitutes for HFCs, can reduce dependence on refrigerant-based systems altogether, supporting both compliance and broader mitigation objectives.

Historically, the Montreal Protocol has benefited greatly from not-in-kind (NIK) transitions in the phaseout of ozone-depleting substances such as chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs).[2] These included solvent alternatives, fire suppressant redesign, and improved insulation materials.

ACTs represent a new generation of not-in-kind (NIK) solutions—expanding the scope of sustainable cooling options beyond chemical substitution. Past examples of NIK measures under the Montreal Protocol include transitioning from halons to inert gas systems for fire suppression, adopting aqueous or no-clean techniques in electronics cleaning, and substituting solvent-based aerosols with mechanical

[2] Carbon Containment Lab. 2024. *Charting a Path for Alternative Cooling Technologies: Opportunities for Alternative Cooling Technologies in the HFC Transition*. Policy brief. Carbon Containment Lab. August 1, 2024. https://carboncontainmentlab.org/publications/act-policy-brief.

alternatives. These interventions not only enabled early compliance but also catalyzed market transformation across multiple sectors.

ACTs continue this trajectory by introducing entirely different cooling principles, such as phase-change, thermoacoustics, magnetism, or radiative heat transfer. These technologies may not fit traditional refrigerant-based categories, yet they hold significant potential for climate impact.

Acknowledging ACTs within the Protocol's innovation history reflects its capacity to adapt to emerging science and engineering advances. Maintaining this openness will be critical as the global demand for cooling rises and the limitations of chemical substitution alone potentially become more evident.

b. Climate Benefits

ACTs offer dual climate benefits by avoiding high-GWP refrigerants and reducing operational energy consumption. Technologies that eliminate or minimize refrigerant use prevent the release of potent greenhouse gases associated with leakage during equipment operation, maintenance, and disposal. Additionally, many ACTs operate at higher intrinsic efficiencies or under passive principles that significantly lower electricity demand.

Radiative cooling panels, for example, reflect solar radiation while emitting infrared heat to the sky, enabling daytime cooling without consuming power. Desiccant-based systems reduce humidity before mechanical cooling is applied, decreasing the total cooling load and allowing for smaller or less energy-intensive systems. In thermoelectric and thermoacoustic devices, the absence of moving parts reduces energy losses and maintenance requirements.

By bypassing refrigerant leakage and improving system performance across diverse use cases, ACTs can enable measurable reductions in both direct and indirect greenhouse gas emissions. These dual benefits—eliminating a high-GWP input and enhancing operational efficiency—make ACTs a powerful complement to existing refrigerant transition strategies under the Kigali Amendment.

c. Compliance Support

In some sectors, particularly those facing logistical barriers to refrigerant servicing or that require extreme temperature control, ACTs may offer the only viable path to long-term compliance. These include applications such as remote or off-grid facilities, high-temperature industrial processes, or ultra-low-temperature refrigeration, where conventional systems face operational and maintenance constraints.

Moreover, certain ACTs—such as air-cycle systems or passive radiative technologies—eliminate the need for refrigerants entirely, sidestepping not only the emissions associated with leaks but also the service and regulatory challenges tied to refrigerant use. Their inclusion in the compliance toolkit broadens the scope of solutions available to Parties and helps ensure alignment with phasedown obligations, even in difficult use cases. In doing so, ACTs enhance the Montreal Protocol's flexibility in achieving phasedown targets under diverse economic and technical conditions.

d. Innovation Ecosystem

ACTs are fueling a growing innovation ecosystem that includes advanced materials science, mechanical engineering, and sustainable architecture. Technologies such as elastocaloric and barocaloric systems draw on progress in solid-state physics, while district-scale systems like lake water cooling reflect innovation in infrastructure planning. By supporting ACTs, the Montreal Protocol reinforces an interdisciplinary model of climate innovation.

e. Energy Efficiency Potential

Several ACTs demonstrate the potential to lower energy demand relative to conventional vapor compression technologies. Thermoelectric devices deliver precise cooling with limited energy input, while sky radiative systems can eliminate active cooling during favorable conditions. These improvements contribute to broader national and global efficiency targets and reduce peak power demand, which is particularly critical in grid-constrained regions.

The development of ACTs has catalyzed cross-sector innovation, involving start-ups, academic research centers, and public-private partnerships. Many technologies—such as elastocaloric and barocaloric systems—have emerged from advanced materials research, while others like lake water cooling built on civil infrastructure and systems engineering. Supporting ACTs strengthens the overall innovation ecosystem aligned with the Montreal Protocol goals.

7. CONCLUSION: "ACT"ING NOW

The Parties to the Montreal Protocol have a unique opportunity to extend the treaty's legacy of climate leadership by recognizing and supporting the potential of ACTs. Great attention and possible action by the Parties would send a clear signal that ACTs are a priority area for innovation, investment, and implementation.

ACTs can complement refrigerant transition strategies and help deliver deeper, faster climate benefits, especially in sectors where conventional approaches face technical or market limitations. Their inclusion in pilot programs, assessment processes, and national policy frameworks will ensure that the global cooling transition is not only efficient and safe but also technologically diverse and resilient.

Looking forward, ACTs can help define a new paradigm for sustainable cooling—embracing a wide range of solutions tailored to local needs and conditions. By 2050, a diversified, resilient, and climate-aligned global cooling sector is achievable. To reach that goal, Parties should act now to mainstream ACTs within the Montreal Protocol framework.

ANNEX A

Examples of ACTs

The following examples represent diverse pathways for implementing ACTs. Each entry highlights a distinct technology category, operational principle, and one or more illustrative innovators. This is provided for informational purposes only and does not imply endorsement or an evaluation of the efficacy of any of the technologies and approaches listed herein.

1. **Active Cooling Technologies**

   a. **Elastocaloric Cooling (Solid-State)**

      i. *Description:* Elastocaloric systems exploit the temperature change that occurs when shape memory alloys (SMAs), such as nickel-titanium, are mechanically stressed and released. These systems operate using mechanical activation of shape memory alloys to create a temperature change, eliminating the need for traditional vapor-compression refrigerants. Their performance is comparable to or potentially better than vapor compression systems, particularly in applications requiring compact, flexible devices.

      ii. *Example:* Exergyn (Ireland) is commercializing its next-generation heat pump systems using SMA-based technology. Applications include HVAC, refrigeration, and transportation.

   b. **Barocaloric Cooling (Solid-State)**

      i. *Description:* Barocaloric cooling uses pressure-induced solid-state phase transitions to transfer heat, eliminating refrigerants and enabling compact designs. Operating within standard HVAC pressure and temperature ranges, barocaloric systems are suited to small- and medium-scale cooling.

      ii. *Example:* Pascal Technologies (USA) has developed barocaloric refrigerants based on metal-halide perovskites and is scaling from laboratory validation to commercial demonstrations.

c. **Magnetocaloric Cooling (Solid-State)**

i. *Description:* Magnetocaloric systems utilize reversible entropy changes in magnetically active materials like gadolinium when exposed to magnetic fields. This enables refrigerant-free cooling, with high temperature differentials achievable in compact systems.

ii. *Example:* MAGNOTHERM (Germany) is developing magnetic beverage coolers and refrigeration units for retail, with plans to extend to hydrogen liquefaction and data center cooling.

d. **Thermoelectric Cooling (Solid-State)**

i. *Description:* Thermoelectric systems rely on the Peltier effect in semiconductors to pump heat across junctions when electric current is applied. Benefits include silent operation, modular design, and zero refrigerants.

ii. *Example:* Phononic (USA) produces ENERGY STAR-certified solid-state refrigerators and thermoelectric cooling systems using bismuth telluride semiconductors. Applications include cold chain logistics, data centers, and LiDAR.

e. **Thermoacoustic Cooling**

i. *Description:* Thermoacoustic devices generate standing sound waves in gas-filled chambers, driving temperature gradients across the medium without moving parts. They offer a refrigerant-free option for residential and light commercial use.

ii. *Example:* BlueHeart Energy (Netherlands) has developed a 6 kW prototype heat pump system using thermoacoustic principles.

f. **Air-based Cooling**

i. *Description:* The Reverse-Brayton cycle uses air (R729) as the refrigerant, with heat exchange achieved via a compander (combined compressor-expander).

This method eliminates the use of fluorinated refrigerants and is capable of reaching ultra-low temperatures.

ii. *Example:* The Korea Institute of Energy Research (South Korea) has demonstrated air-based cooling to −60°C in laboratory systems, with potential applications in pharmaceuticals and semiconductors.

2. **Passive Cooling Technologies**

   a. **Radiative Cooling**

      i. *Description:* Radiative cooling panels reflect solar radiation and emit infrared radiation to the sky, achieving sub-ambient temperatures without electricity. These systems can operate day and night.

      ii. *Example:* SkyCool Systems (USA) has installed radiative panels in commercial settings, and has reported energy reductions up to 90% in specific use cases when used as a full-system replacement.

   b. **Advanced Building Design**

      i. *Description:* Architectural cooling approaches utilize natural ventilation, high-mass materials, shading structures, and reflective surfaces to reduce indoor temperatures without mechanical systems.

      ii. *Example:* Kéré Architecture (Burkina Faso) incorporates stabilized clay and passive design strategies in community buildings, eliminating the need for air conditioning.

   c. **Two-phase Cooling Systems**

      i. *Description:* which transfer heat through evaporation and condensation of a working fluid in sealed channels, using passive capillary action without pumps or moving parts.

      ii. *Example:* Calyos (Belgium) delivers pump- and fan-free cooling using space-grade passive two-phase systems, like Loop and Pulsating Heat Pipes, for efficient, silent, and maintenance-free heat transfer.

3. **Hybrid Cooling Systems**

    a. **Desiccant-based systems**

        i. *Description:* Liquid desiccant systems dehumidify air using salt solutions, reducing latent cooling loads and enabling smaller active cooling systems. These systems can also shift cooling loads to off-peak hours.

        ii. *Example:* Blue Frontier (USA) combines liquid desiccants with indirect evaporative cooling. Pilot installations are ongoing in commercial buildings.

    b. **Phase-change material (PCM) systems**

        i. *Description:* PCMs store and release thermal energy by transitioning between solid and liquid states. These systems can shift cooling loads by storing nighttime cold for use during peak daytime demand. PCMs are used in building-integrated applications for thermal buffering and are being evaluated for use in residential and commercial load management.

        ii. *Example:* Calion Technologies (USA) is developing a 5 kW ionocaloric heat pump with 40 kWh thermal storage as a novel, drop-in alternative to vapor compression, backed by the California Energy Commission.

    c. **Ocean Water, Lake, and Groundwater Cooling Concepts**

        i. *Description:* Hydronic district cooling systems extract stable-temperature water from lakes or oceans to supply chilled water to buildings. Heat is removed through closed-loop exchangers, with water returned to the source.

        ii. *Example:* The GeniLac project (Switzerland) has delivered renewable cooling to over 70 buildings, including UN facilities, using Lake Geneva since 2009.