Paving India's Pathway to HFC Phasedown

The Emerging Issue of PFAS Pollution and Learning from the Global Developments

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Executive summary

India has a strategic opportunity to lead a sustainable and future-proof refrigerant transition by prioritising low environmental impact technologies and building a strong supportive ecosystem. The choice India makes now will shape its cooling sector for decades. India's HFC phase-down begins with a freeze in 2028, and it is developing its phase-down strategy at a time when evidence on the health and environmental risks of HFOs is emerging. This brief examines whether India should transition via HFOs and their blends, or leapfrog directly to natural refrigerants. This transition is governed by the Montreal Protocol on Substances that Deplete the Ozone Layer, an international treaty adopted in 1987 (to which India acceded in 1992), and its subsequent amendments, particularly the Kigali Amendment in 2016 (which India ratified in 2021).

This has led to a progressive shift in refrigerant choices from chlorofluorocarbons (CFCs) to hydrochlorofluorocarbons (HCFCs), then to hydrofluorocarbons (HFCs), and now towards low global warming potential (GWP) alternatives. While earlier phases of refrigerant transition were driven by the ozone depletion potential (ODP) of refrigerant gases, the next phase is driven by GWP, following India's ratification of the Kigali Amendment. However, there is now a growing need to also consider broader environmental risks associated with these new refrigerants and their degradation products.

Some of these new refrigerants decompose to form trifluoroacetic acid (TFA), a per- and polyfluoroalkyl substance (PFAS), the potential environmental and health impacts of which were not well understood or communicated until recently. These are synthetic chemicals that resist natural degradation and accumulate endlessly in the environment (therefore, they are called 'forever chemicals'). There is emerging scientific evidence of their adverse impacts on food systems and human health.

The varying environmental profile of different refrigerant groups, including their ODP, GWP_{100} (calculated over 100-year time horizon), and tendency to decompose to TFA, are detailed in Table ES1.

Table ES1. Characteristics of different refrigerant groups

Group	Full name	Example	ODP	GWP_{100}	Decomposing to TFA
CFC	Chlorofluorocarbons	R11	1.0	6,230	No
HCFC	Hydrochlorofluorocarbons	R22	0.055	1,960	No
HFC	Hydrofluorocarbons	R134a	0	1,530	Yes
HFO	Hydrofluoroolefins	R1234yf	0	0.501	Yes
Natural refrigerants	--	R290	0	0.02	No

Source: IPCC. 2024. "IPCC Global Warming Potential Values."

Broadly, two categories of refrigerants have emerged as potential replacements to high-GWP HFCs: so-called hydrofluoroolefins (HFOs) and natural refrigerants. The HFOs have low GWP and zero ODP; however, their market introduction has raised significant environmental, health, and regulatory concerns. The major issues associated with HFOs are their contribution to PFAS pollution, their tendency to break down into the super-pollutant R-23 (GWP 14,600) (Garry 2024), and the implications of patents and intellectual property rights (IPR), which may limit access, increase costs, and create market dependencies. Some Non-Article 5 countries, such as European nations, which initially transitioned to HFOs, have now jointly proposed restrictions on PFAS, including HFOs, which are now under review (ECHA 2026).

Natural refrigerants, like the fluorinated gases (F-gases, like HFCs and HFOs) they replace, require proper safety management in all phases of the equipment lifecycle due to associated safety risks. However, these risks can be effectively addressed with technological advancements in design, along with proper operation and maintenance guidelines. This provides an opportunity for Article 5 countries such as India (whose phase-down schedule is yet to start) to leapfrog directly to the adoption of natural refrigerants, thereby bypassing the intermediary transition step of HFOs, which may represent an unnecessary environmental burden.

Accordingly, when developing the HFC phase-down strategy, a thorough analysis of the following factors should be undertaken in consultation with relevant stakeholders:

- **Refrigerant transition involves significant investment and is a resource-intensive process, making the long-term sustainability of the transition critical (TEAP 2026).** The transition should be future-proof, ensuring that addressing one challenge (such as GWP) does not create another problem (e.g. environmental and health risks with TFA/PFAS).

- **A comprehensive understanding of the lifecycle impacts of alternative refrigerants is essential.** This includes evaluating the alternatives on parameters such as energy performance, climate impacts, chemical persistence, toxicity, system reliability, economic feasibility, other environmental impacts, safety, human health, equitable access to technologies, and the risk of dependence on specific technologies or suppliers.
- **Establishing a supportive ecosystem is crucial for a smooth and effective refrigerant transition.** This will involve ensuring access to technical and financial assistance for upgrading the supply chain, training and certification of the workforce, developing standards and standard operating procedures (SOPs), strengthening safety frameworks, building awareness among key stakeholders, and promoting collaboration across the value chain.

India has a strategic opportunity to lead a sustainable and future-proof refrigerant transition by prioritising low environmental impact technologies and building a strong supportive ecosystem.

1. Introduction

India is developing its HFC phase-down strategy to sustainably transition to low-GWP alternatives, in line with its commitment under the Kigali Amendment to the Montreal Protocol. The phase-down schedule for India starts in 2028, with the aim to reduce HFC consumption, in GWP-equivalent terms, by 85 per cent of the baseline by 2047 in a phased manner. India's experience with refrigerant transition is not new; the country has successfully navigated through a few generations of refrigerant transition before, from CFCs to HCFCs to HFCs, and is now gearing up for the next phase to meet its Kigali commitments.

1.1 The journey of refrigerant transitions and the Montreal Protocol

In the 19th and early 20th centuries, the first generation of refrigerants consisted of naturally occurring substances such as ammonia (NH_3), carbon dioxide (CO_2), sulphur dioxide (SO_2), methyl chloride (CH_3Cl), and even water and air. These compounds were chosen primarily for their thermodynamic properties and wide availability. However, many of these early refrigerants posed significant toxicity, flammability, or pressure risks, raising significant safety concerns that limited their widespread adoption (Pavkovic 2013).

The search for safer, more stable refrigerants led to the development of synthetic chemicals by the late 1920s, marking the advent of CFCs, which also had safety challenges. However, they were not addressed at that time; CFCs were non-flammable, partly non-toxic if not exposed to high temperatures, and highly stable, making them ideal for refrigeration, air conditioning, aerosol propellants, foam blowing agents, and solvents. Their inertness and low pressures, which was their greatest perceived strength, allowed for their widespread adoption in countless consumer and industrial products throughout the mid-20th century.

In the 1970s, it was discovered by Molina and Rowland (1974) that CFCs were causing significant damage to the stratospheric ozone layer, which protects life on Earth from harmful ultraviolet (UV) radiation (Molina and Rowland were awarded a Nobel Prize in 1995 for this discovery). Recognising the urgency of the need to protect the ozone layer, the global community responded to the ozone crisis with the Vienna Convention for the Protection of the Ozone Layer (1985), followed by the Montreal Protocol on Substances that Deplete the Ozone Layer, adopted in 1987. The Montreal Protocol is widely recognised as one of the most successful international environmental agreements in history. The Protocol mandates a gradual, stepwise reduction in the production and consumption of ozone-depleting substances (ODSs), with specific timelines for Article 5 and Non-Article 5 countries. This landmark treaty led to the systematic phase-out of ODSs, and has guided the world through a series of refrigerant transitions, each with its own challenges and environmental trade-offs (Ozone Secretariat 2020).

The initial substitutes for the CFCs were HCFCs, which have significantly lower ODP (typically in the range of 0.01 to 0.1) as compared to that of CFCs (which have an ODP of 1.0 or higher). They were, therefore, designated as 'transitional substances' under the Protocol, intended for temporary use until better, non-ozone-depleting alternatives could be developed. The Montreal Protocol set a phase-out schedule for HCFCs, with Non-Article 5 countries having completed their phase-out by 2020 and Article 5 countries required to do so by 2030. India successfully phased out CFCs by 2010, and is on track to phase out HCFCs by 2030.

Refrigerants containing ODSs were replaced by HFCs as they are supposed to be a more environment-friendly alternative-HFCs do not harm the ozone layer and have become widely used globally. However, most HFCs have an exceptionally high GWP, up to thousands of times higher than CO_2, and a long atmospheric lifetime. As a result, they contribute significantly to the rise in global temperatures. Therefore, in 2016, another international agreement, the Kigali Amendment to the Montreal Protocol, was adopted, under which world leaders agreed to phase down the production and consumption of HFCs and subsequently replace them with low-GWP refrigerants. The amendment introduced legally binding schedules to progressively reduce the HFC consumption for Non-Article 5 countries (85 per cent by 2036) and Article 5 countries (80–85 per cent by 2045/2047) (Ozone Secretariat 2020).

This transition is primarily guided by the GWP of refrigerant gases, with two broad categories of low-GWP alternatives emerging: HFOs and natural refrigerants. Concerns beyond global warming spanning environmental, health, and safety impacts are now emerging around the adoption of these refrigerants. The use of HFOs initially gained traction in Non-Article 5 countries where the phasedown schedule has already started. However, HFOs break down into TFA, a PFAS that persists indefinitely in the environment and human body, earning PFAS the name 'forever chemicals'. Scientific evidence is now emerging about their adverse impacts on food systems and human health; therefore, efforts are now underway to restrict the use of HFOs and transition to natural refrigerants. This transition aims to avoid the accumulation of forever chemicals in the environment and in the human body.

Natural refrigerants have been used since the introduction of mechanical refrigeration more than a hundred years ago. All refrigerants require proper safety measures throughout their operational lifecycle; however, these risks can be addressed through technological advancements and adherence to standards in system design, operation, and maintenance. This provides an opportunity for Article 5 countries like India, whose phase-down schedule is yet to start, to leapfrog directly to a clean and long-term solution with natural refrigerants, bypassing the intermediary step of HFOs.





Auto mechanic using pressure gauge on air compressor.

1.2 Objectives of this policy brief

India is intensifying its preparations for the next phase of refrigerant transition, including the development of its HFC phase-down strategy. A key question is whether India should follow a gradual transition path via HFOs and their blends, or leapfrog directly to natural refrigerants, which have been shown to be viable and associated with lower environmental and health risks.

The objectives of this policy brief are to:

- Assess the advantages, suitability, concerns, and issues associated with adopting low-GWP alternatives (both synthetic and natural refrigerants) that emerged as replacement for HFCs.
- Inform the development of a suitable and sustainable transition pathway for India that supports global competitiveness, while avoiding lock-in to technologies facing emerging regulatory or environmental restrictions.

This brief focuses specifically on vapour-compression refrigeration and air-conditioning systems, given their dominant share of India's current cooling demand. Non-vapour-compression alternatives-such as evaporative, desiccant, and absorption cooling offer complementary energy saving potential, particularly in dry climates, but fall outside the scope of this brief.

1.3 Refrigerant market trends

India is currently one of the fastest-growing markets for cooling equipment in the world, and this has driven up the demand for refrigerants. The *India Cooling Action Plan* (MoEFCC 2019) estimates that the annual refrigerant demand will grow 7-8 times from ~24,300 MT in 2017-18 to ~181,000 MT in 2037–38 (Table 1). The Indian refrigerant market is currently dominated by HFCs, which were initially adopted as replacements for ODSs like CFCs and HCFCs, in accordance with the Montreal Protocol. However, the high GWP of HFCs has prompted a global movement towards phasing them down under the Kigali Amendment to the Montreal Protocol; the EU has set a target to fully phase out F-gases by 2050 (F-Gas Regulation 2024/573), with the earlier phase-down regulation (517/2014) now superseded by this stricter phase-out framework. India, as a signatory to the Kigali Amendment, is committed to gradually reducing its HFC consumption, necessitating the exploration and adoption of alternative refrigerants with lower environmental impact. Key sectors using refrigerant gases include:

- **Room air conditioners (RAC):** This is the largest consumer of refrigerants in India. Most room ACs in India currently use HFC-32 or HFC-410A, with the former having significant market share (~90 per cent) because of its lower GWP and better energy efficiency.
- **Refrigerators:** Domestic refrigerators have largely transitioned to hydrocarbon refrigerants like R-600a (isobutane), which are climate-friendly and energy efficient. This transition has been successful due to safety protocols and improved technology.
- **Commercial refrigeration and cold chains:** This sector uses a variety of refrigerants, including HFC-134a, HFC-404A, and natural refrigerants like ammonia (R-717) and CO_2 (R-744) in larger applications.
- **Commercial/industrial air conditioning and chillers:** These use a mix of HFCs and HCFCs (like HCFC-22), with a smaller share adopting low-GWP alternatives or natural refrigerants, depending on the application and cost considerations.
- **Mobile air conditioning (MAC):** The automobile sector primarily uses HFC-134a; however, the models manufactured in India for export (for example to the European markets) use HFO-1234yf, decomposing 100 per cent to TFA in the atmosphere.
- **Heat pumps:** This is a nascent segment in India compared to cooling-only applications. Heat pumps are gaining traction for water heating and industrial process heat (e.g., dairy and textiles). These systems currently use HFC-410a, HFC-407C, HFC-134a, and HFC-32, with propane (R-290) and CO_2 (R-744) emerging as natural alternatives in this segment.

These are summarised in Table 2.

Table 1. Estimated future refrigerant demand in India

Year	Annual refrigerant production (MT)
2017–18	24,300
2022–23	40,500–45,500
2027–28	68,500–75,500
2037–38	166,000–181,000

Source: MoEFCC. 2019. India Cooling Action Plan. Ministry of Environment, Forest, and Climate Change, Government of India.

Table 2. Prevalent refrigerants in various applications and potential low-GWP alternatives

Key refrigerant consuming sectors	Current refrigerants in use (GWP), [PFAS yield]	Potential alternatives (GWP), [PFAS yield]	ISHRAE assessment of low GWP options for India (lowest GWP feasible options that provide high energy efficiency)
Room air conditioners mini-split and window air conditioners	HFC-32 (771) [0] HFC-410a (2,256) [0] HCFC-22 (1,960) [0] R-290 (0.02) [0]	HFC-32 (771) [0] R-290 (0.02) [0] HFC-444B (295) [up to 10%] HFC-454B (531) [up to 30%]	R-290, R-32
Domestic refrigerators	R-600a (0.006) [0] HFC-134a(1,526) [up to 20%]	R-600a	R-600a

Key refrigerant consuming sectors	Current refrigerants in use (GWP), [PFAS yield]	Potential alternatives (GWP), [PFAS yield]	ISHRAE assessment of low GWP options for India (lowest GWP feasible options that provide high energy efficiency)
Commercial (large scale) air conditioning **1. Ducted packaged AC** **2. Scroll chillers** **3. VRF** **4. Screw & centrifugal chillers**	HFC-410A HFC-407C (1,908) [up to 20%] HFC-32 HFC-134a HCFC-123 (90.4) [0]	HFC-452B (779) [up to 26%] HFC-444B R-454B R-290 R-717 (0) [0] R-744 (1) [0]	HFC-32 HFC-452B R-717 R-454B
Commercial refrigeration **1. Display cabinets** **2. Vaccine/medical storage** **3. Cold storage**	HFC-404A (4,728) [up to 20%] HFC-134a R-600a	R-290 R-600a HFO-1234yf (0.501) [100%] R-717 R-744	Non-flammable: R-448A, R-449A
Mobile air conditioning	HFC-407C HFC-134a	HFC- 152a (164) [0] HFO-1234yf R-290	R-290
Heat pumps **1. Air to water** **2. Water to water**	HFC-410A HFC-134a HFC-407C	HFC-32 R-290	HFC-32 R-290

Source: Shaligram, Avinash. 2025. ISHRAE Position Document on Refrigerants for Indian Refrigeration and Air Conditioning Industries: Challenges and Responsibilities.

1.4 Policies and regulations influencing refrigerant choices in India

India's refrigerant choices are significantly influenced and impacted by a combination of international agreements, and domestic policies and regulations. These policies primarily aim to (a) phase out substances that deplete the ozone layer and those that contribute to global warming, and (b) enhance energy efficiency of the cooling systems.

The following are the main policy drivers:

International agreements (and India's commitments)

- **The Montreal Protocol on Substances that Deplete the Ozone Layer, 1987** (Ozone Secretariat 2020)**:**
    - This protocol mandates the phase-out of ODSs like CFCs and HCFCs.
    - India became a party to the Montreal Protocol in 1992.
    - CFCs: India successfully phased out CFCs by 2010.
    - HCFCs: India is currently in the process of phasing out HCFCs under the *Hydrochlorofluorocarbon Phase-out Management Plan* (HPMP). The goal is a complete phase-out by 2030 (with a service tail of 2.5 per cent annual average during the period 2030–40). Significant reductions have already been achieved in HCFC use, including a complete phase-out of HCFC-141b in foam manufacturing, with its import banned from 1 January 2020. Another HCFC, R-22, remain widely used in older ACs but is being phased out under HPMP stage III (2023–30), which mandates that new equipment using HCFCs be discontinued by 31 December 2024, ahead of full phase-out (with the 2.5 per cent servicing allowance) by 2030 (MoEFCC 2024).

- **Kigali Amendment to the Montreal Protocol, 2016** (Ozone Secretariat 2020)**:**
    - This amendment focuses on the phase-down of HFCs, which, while not ozone-depleting, are potent greenhouse gases.
    - India ratified the Kigali Amendment in 2021.
    - India's HFC phase-down schedule:
        - Freeze in consumption by 2028 (relative to baseline years of 2024, 2025, and 2026)
        - Systematic reductions starting with a 10 per cent cut by 2032 and gradually progressing to cumulative reductions of 20 per cent by 2037, 30 per cent by 2042, and an 85 per cent cut by 2047.
    - This drives the industry towards low-GWP alternatives.

Domestic policies and regulations:

- **The *Ozone Depleting Substances (Regulation and Control) Rules, 2000* (and subsequent amendments)** (MoEFCC 2000)**:**
    - Established under the *Environment (Protection) Act, 1986*, these rules are India's legal framework to implement its Montreal Protocol obligations.
    - They regulate the production, consumption, import, export, sale, purchase, and use of ODSs.
    - The rules have been amended periodically to align with accelerated phase-out targets, including those for HCFCs.
    - Amendments are expected to control HFC production and consumption in line with the commitments made under the Kigali Amendment.
    - These rules also mandate licencing for import/export of controlled substances.
- ***India Cooling Action Plan (ICAP)*** (MoEFCC 2019)**:**
    - India was one of the first countries to launch a national cooling action plan.
    - It provides a comprehensive, multi-sectoral strategy with a 20-year horizon (2017–18 to 2037–38), aiming to:
        - Reduce cooling demand across sectors by 20–25 per cent.
        - Reduce refrigerant demand by 25–30 per cent and enable transition to non-ODS and low-GWP alternatives.
        - Enhance energy efficiency in cooling appliances and systems, and reduce cooling energy requirement by 25–40 per cent.
    - While refrigerant-agnostic, *ICAP* promotes 'sustainable' and 'climate-friendly' choices.
- ***Bureau of Energy Efficiency (BEE) Standards and Labelling Programme*** (BEE 2025)**:**
    - The BEE mandates minimum energy performance standards for various appliances and provides star ratings from 1-star to 5-star based on their energy efficiency performance, with 1-star being the least and 5-star being the most efficient. The *Minimum Energy Performance Standard* (MEPS) and criteria for star ratings are periodically revised to ensure improvements in the energy efficiency.
    - Star rating is mandatory for several cooling appliances such as RACs, refrigerators, chillers, and light commercial air conditioners. This now also includes information on refrigerant type and its GWP.
    - This encourages consumers and manufacturers to choose more energy efficient appliances that utilise climate-friendly refrigerants.
- Bureau of Indian Standards (BIS) safety standards:
    - The BIS has adopted safety standards for natural refrigerants, under IEC 60335-2-40:2018 and MED 3 (14430) in 2020. This is crucial for the safe adoption of these low-GWP flammable hydrocarbons like R-290 (propane) and R-600a (isobutane), and toxic, mildly flammable R-717 (ammonia).

- ***E-waste Management Rules*** (MoEFCC 2022)**:**
    - These rules mandates for proper recovery and disposal of refrigerants at the end of an appliance's life, to prevent the harmful emissions.
    - Several cooling devices such as RACs are categorised as 'Electrical & Electronics Waste' under these rules, falling under extended producer responsibility (EPR).
    - Although these rules do not directly dictate initial refrigerant choice, they influence it indirectly. The refrigerant-management processes and associated compliance costs that manufacturers must bear are variable, depending on the refrigerant selected.

India's refrigerant choices are primarily influenced by its obligations under the Montreal Protocol and the Kigali Amendment, national action plans like *ICAP*, and regulatory measures on energy efficiency and safety. Now India is in the process of developing its HFC phase-down strategy in compliance with the Kigali Amendment, which will influence the next generation of transition from high-GWP HFCs to low-GWP alternatives. New scientific evidence requires actions for a supported leapfrog scenario towards natural refrigerants in all sectors to avoid additional health risks and costs for society, due to counter measures of removing TFA from drinking water, etc.

1.5 Low-GWP refrigerants as alternatives

The Kigali Amendment has accelerated the transition towards a new generation of refrigerants with ultra-low-GWPs. The industry is exploring and adopting several alternatives that can be broadly classified under two categories:

- **Natural refrigerants:** These are substances that occur naturally in the biosphere and have very low-GWPs and zero ODPs. Some of the energy efficient examples of natural refrigerants applied since 1880 are:
    - Carbon dioxide (CO_2/R-744)
        - GWP of 1, PFAS = 0.
        - Non-flammable and non-toxic.
        - Requires dedicated design and equipment.
        - Compact sizing due to fluid properties, related to density and operational pressures.
        - A common fire-extinguishing fluid and widely used for carbonating beverages.
        - Over 1 million R-744 heat pump compressors produced for EVs by Hanon Systems.
        - Over 10 million R-744 hot water heat pumps are installed in Japanese households.
    - Ammonia (NH_3/R-717)
        - GWP of 0, PFAS = 0.
        - Highly energy efficient refrigeration and heat pump systems, used mainly in industrial refrigeration since the 1880s.
        - Safety measures are widely applied and understood by end-users.
    - Hydrocarbons (e.g., Propane R-290, Isobutane R-600a)
        - GWPs of <1, PFAS = 0.
        - Highly energy efficient and widely available.
        - Require safety measures and charge limitations, which depend on system access and installation location.
        - Safety standards support vendors and end-users in performing proper risk assessments.
    - Water (H_2O/R-718)
        - GWP of 0, PFAS = 0
        - Non-flammable and non-toxic.
        - Requires specialised, high-vacuum compressor design due to water's low vapour density and sub-atmospheric operating pressures.
        - Still an emerging technology, with companies such as Efficient Energy (Germany) and Oxicool (USA) developing water-based chillers and air-conditioning systems for data centres, industrial cooling, and buildings.

- **Hydrofluoroolefins (HFOs):** These are synthetic refrigerants that contain hydrogen, fluorine, and carbon, but also have at least one double bond in their molecular structure. This double bond makes them much less stable in the atmosphere, leading to very short atmospheric lifetimes, and by this definition, on a 100-year perspective, extremely low-GWPs (typically less than 10). Examples include R-1234yf and R-1234ze. They have been applied in automotive air conditioning, chillers, and some commercial refrigeration applications; they are mildly flammable (A2L classification) which means they require the same safety measures as other flammable fluids. They breakdown in the atmosphere to TFA (PFAS) or HFC 23, a super pollutant.

In addition to these, many modern systems use low-GWP blends of various refrigerants (e.g., HFC/HFO blends) to achieve optimal performance, safety, and environmental profiles for specific applications.

2. HFOs as a low-GWP alternative: PFAS and other concerns

The HFOs are a class of synthetic refrigerants developed to address the environmental concerns associated with earlier generations of refrigerants, notably CFCs, HCFCs, and HFCs. With increasing pressure to reduce greenhouse gas emissions and comply with international climate agreements like the Kigali Amendment to the Montreal Protocol, HFOs have emerged from the chemical industry as a prominent class of low-GWP and zero-ODP refrigerants, promoted as replacements for HFCs and HCFCs in various refrigeration and air conditioning applications. The most widely used HFOs today include:

- HFO-1234yf: Primarily used in MAC systems as a drop-in replacement for HFC-134a (100 per cent converts to PFAS) (Chele et al. 2024).
- HFO-1234ze(E): Used in stationary air conditioning and refrigeration, as well as in foam blowing and aerosol applications (30 per cent converts to PFAS).
- HFO-1233zd(E): Used in centrifugal chillers and foam blowing agents (30 per cent converts to PFAS).
- Blends (e.g., R-452A, R-513A, R-449A): These are mixtures of HFOs and HFCs to balance flammability, GWP, and performance (26 per cent, 65 per cent, and 30 per cent convert to PFAS).

In addition to low-GWP and zero-ODP, many HFOs and HFO-blends offer comparable thermodynamic properties and energy efficiency to the HFCs they replace. This means that a transition to HFOs often does not necessitate a compromise in system performance or an increase in energy consumption, which is crucial for widespread adoption. For example, HFO-1234yf has thermodynamic properties remarkably similar to HFC-134a, making it a 'drop-in' or near 'drop-in' replacement in many systems, particularly in MAC (EFCTC n.d.). However, service technicians face significantly higher refrigerant costs, which are passed on to consumers through more expensive repairs and maintenance.

2.1 The emerging issue of PFAS pollution

The adoption of HFOs has raised significant environmental, health, and regulatory concerns (Arp et al. 2024). They are also mildly flammable, but the major issue associated with their use is that they decompose into TFA, a PFAS known for its environmental persistence. These PFAS are a group of synthetic chemicals known for their exceptional persistence in the environment; they resist breakdown by natural processes and can accumulate in water bodies, soil, and even living organisms, including humans, posing risks to the ecosystems and human health. This has earned them the moniker 'forever chemicals'.

Chemicals such as HFO-1234yf and HFO-1234ze(E) break down in the atmosphere and convert to TFA. While TFA can also be a byproduct of HFC degradation, HFOs are reported to produce significantly higher quantities of TFA (e.g., HFO-1234yf yields up to five times more, i.e. 100 per cent, TFA than HFC-134a for the same amount of substance). This raises serious concerns about the increasing concentration of TFA in fresh water sources, including rivers, lakes, and even drinking water, dairy products, mother's milk, etc. **Globally, refrigerants are responsible for more than 60 per cent of the global PFAS pollution** (ChemSec 2024).

Studies have linked certain PFAS to a range of adverse health outcomes (US EPA 2024), including:

- Cancer: Increased risk of kidney, testicular, pancreatic, breast, and liver cancers.
- Immune system dysfunction: Weakened immune responses, reduced vaccine efficacy, and increased susceptibility to infections.
- Developmental issues: Low birth weight, developmental delays, and behavioural problems in children exposed prenatally or in early life.
- Endocrine disruption: Interference with thyroid hormone regulation, potentially leading to hypothyroidism, and other metabolic disorders.
- Liver damage: Consistent evidence of liver damage in humans and rodents.

2.2 The classification divide: Debate around the categorisation of TFAs as PFAS

The atmospheric breakdown of modern refrigerants (including HFOs and some of the HFCs) results in the formation of TFA, a short-chain PFAS containing one fully fluorinated methyl or methylene carbon atom. While it technically meets the broader structural definitions of a PFAS, globally there is a debate initiated by the chemical companies over whether it should be regulated under the same restrictive 'forever chemicals' framework. Global regulatory bodies use conflicting boundaries to define what constitutes a PFAS, creating a fragmented regulatory environment.

- **The OECD & EU approach**: The Organisation for Economic Co-operation and Development defines PFAS broadly as any chemical containing at least one fully fluorinated methyl or methylene carbon atom (OECD 2021). Under this structure, TFA is unambiguously classified as a short-chain PFAS. The European Chemicals Agency (ECHA) mirrors this definition (ECHA 2023) and several European countries have advised their national environmental agencies to support ECHA, introducing a universal PFAS restriction that would restrict the use of all chemical precursors that degrade into TFAs.
- **The US EPA approach**: The US Environmental Protection Agency employs a stricter structural requirement that excludes single-carbon and short chains like TFAs from its primary PFAS definitions (US EPA 2025). Consequently, TFA is excluded from the regulatory limits imposed on long-chain variants of PFAS (like perfluorooctanoic acid, PFOA, and perfluorooctanesulfonic acid, PFOS) in the United States.

While the US EPA does not include TFAs under its narrower definition of PFAS, several of the country's state governments (at least 23 states including California, Maine, Minnesota, etc.) adopt the broader definition of PFAS and categorise TFA and PFAS under their regulatory framework (ATMOsphere 2024a).

The US EPA has prioritised legacy, long-chain PFAS (like PFOA and PFOS) which are known for bioaccumulating in human tissue. Unlike long-chain PFAS, TFA is highly water-soluble, highly mobile, and is excreted by the human body much faster, leading the US EPA to treat it as a distinct toxicological profile. Even though TFA may not bioaccumulate in humans as heavily as PFOA, it is completely non-biodegradable ('forever') and progressively accumulates in local water basins. The recent mammalian toxicity studies also indicate that high exposure to short PFAS like TFA may contribute to liver toxicity and reproductive risks (Arp et al. 2024). Thus, the EU, OECD, and several state governments of the USA adopt a broader definition of PFAS and include TFA under the regulatory restrictions on PFAS.

Around 150 scientists and experts on PFAS from across the globe have published a joint statement arguing in favour of the broader definition of PFAS adopted by the OECD and EU categorising TFA as PFAS (Safer States 2024).

2.3 EU proposal to restrict the use of PFAS

A proposal to restrict the use of PFAS was officially submitted to the ECHA (2026). The proposal aims to significantly curtail the manufacture, use, and market-placement of over 10,000 PFAS compounds under the stringent REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) Regulation. This ambitious proposal, spearheaded by Denmark, Germany, the Netherlands, Norway, and Sweden, has since undergone extensive scientific evaluation, stakeholder consultations, and revision. The ECHA's committees are expected to conclude their assessment and deliver final opinions by the end of 2026. Based on the two final opinions, the Commission will propose a restriction for discussion and vote in the REACH Committee, composed of EU Member States.

If adopted, this would be one of the most comprehensive chemical bans ever implemented under the REACH Regulation, and a landmark achievement in the EU's efforts to protect human health and the environment from persistent pollutants. It should, however, be noted that the restriction is expected to allow time-limited derogation for specific PFAS uses where no suitable alternatives are currently available, subject to additional risk-management measures to minimise ongoing emissions. Even though the REACH Regulation applies only within Europe, it will also have a significant impact on the refrigerant choices worldwide due to its influence on global supply chains and markets.

2.4 Status of PFAS issue in India

The PFAS issue is increasingly becoming important in India and is emerging as a critical environmental and public health concern. The National Green Tribunal (NGT) has initiated a *suo motu* case in response to an IIT Madras study highlighting widespread PFAS pollution in Chennai" waterbodies and drinking water (Srinath M. 2024). The NGT directed the Ministry of Environment, Forest and Climate Change (MoEFCC) and the Central Pollution Control Board (CPCB) to prescribe regulatory standards to restrict PFAS pollution, and to monitor and prevent hazardous impacts on public health. The BIS has adopted standards for monitoring of the PFAS pollution, and is in the process of formulating standards prescribing limiting concentrations of PFAS in various water bodies. The Food Safety and Standards Authority of India (FSSAI) released the draft *Food Safety and Standards (Packaging) Amendment Regulations, 2025*, proposing to prohibit PFAS in food contact materials including packaging (FSSAI 2025). This amendment is expected to come into force by the end of 2026.

2.5 Additional concerns related to HFO use

The following are the other key concerns related with the use of HFOs are their potential breakdown into super-pollutant R-23, and the implications of patents and intellectual property rights (IPR).

Breakdown into HFC-23: a super-pollutant

Recent research has identified another troubling pathway: certain HFOs, specifically HFO-1234ze(E), HFO-1336mzz(Z), and HFO-1243zf, can react with ozone in the atmosphere to produce HFC-23 (trifluoromethane), a greenhouse gas with a GWP of 14,600—far higher than the HFOs themselves. HFO-1234ze(E) was found to generate more than eight times as much HFC-23 as the other tested HFOs in laboratory conditions. Even if the overall yield is small, the extremely high-GWP of HFC-23 means its formation can significantly increase the effective climate impact of these HFOs. The discovery that HFOs can indirectly contribute to high-GWP emissions complicates their status as 'climate-friendly' alternatives and raises questions about their long-term suitability under international climate agreements (Garry 2024).

Patents and IPR

The commercialisation of HFOs is heavily controlled by a small number of multinational corporations through a series of patents covering the chemicals themselves, their blends, and their applications in refrigeration systems. The patents have been granted not only on the chemical composition of HFOs (e.g., HFO-1234yf, HFO-1234ze) but also on their use in specific applications such as MAC systems. These patents effectively create a monopoly, limiting the ability of companies in Article 5 countries like India to manufacture or sell HFOs or their blends without licencing agreements. This can stifle competition and innovation, potentially keeping prices high, and restricting access to new technologies in developing markets (Chaturvedi et al. 2016; Seidel and Ethridge 2016; Bhushan 2016).

The ongoing transition to HFOs is driven by the need to reduce global warming and ozone depletion impacts; however, significant concerns remain regarding their impacts on environment and public health. Their PFAS classification, degradation into persistent pollutants like TFA and HFC-23, and the monopolistic control of their intellectual property raise legitimate concerns about their long-term sustainability as an alternative for low-GWP refrigerants.

3. Natural refrigerants as a long-term sustainable alternative

Natural refrigerants, such as hydrocarbons (HCs), ammonia (NH_3), and carbon dioxide (CO_2), are emerging as viable, climate-friendly alternatives to traditional high-GWP refrigerants like HFCs and HCFCs.

3.1 Status of adoption of natural refrigerants in India

The adoption of natural refrigerants varies significantly across different demand segments in India, largely influenced by technical feasibility, safety concerns, cost implications, and market readiness.

Industrial and commercial refrigeration

Ammonia is the dominant refrigerant in industrial refrigeration in India, particularly in large cold storage, food processing, and dairy sectors. Its high efficiency and zero GWP make it a preferred choice, especially where safety and technical expertise are available. There is also a gradual uptake of CO_2 systems, especially in new facilities, but penetration remains limited due to higher initial costs and the need for specialised technical skills. The commercial refrigeration segment (supermarkets, retail, hospitality) is witnessing a slow but growing adoption of hydrocarbons and, to a lesser extent, CO_2 systems, with NH_3 still used in some larger installations. Hydrocarbon-based plug-in cabinets and display cases are also being introduced.

Challenges: Safety concerns, lack of skilled personnel (except for ammonia systems), lack of awareness, and higher upfront costs for advanced systems.

Domestic refrigeration

This segment has seen perhaps the most significant and early adoption of natural refrigerants, primarily isobutane (R-600a). Indian manufacturers, driven by global trends and relatively low charge sizes required for domestic refrigerators, have largely transitioned to R-600a. This refrigerant offers excellent energy efficiency and has a negligible GWP. The transition was aided by the fact that the inherent flammability of R-600a could be managed effectively, with relatively small charge limits and design modifications. This segment serves as a success story for natural refrigerant adoption in India.

Challenges: Minimal, as the technology is mature and safety risks are manageable in small charge systems.

Air conditioning (residential and commercial)

The adoption of natural refrigerants in air conditioning is at a nascent stage. The majority of the market still relies on HCFCs and HFCs. With technical and financial support available from the Multilateral Fund (MLF), assistance has been extended to Godrej & Boyce Manufacturing Co. Ltd. under India's HPMP for the development and commercialisation of R-290 (propane) based RACs R-290 not only has zero ODP and ultra-low-GWP (around 0.02), but also offers superior thermodynamic performance. However, uptake is limited.

Challenges: As with LPG cylinders already used across Indian households, R-290 AC units, like R-32 units, require dedicated safety standards, revised installation practices, and enhanced technician training. The perception of risk among consumers, very limited familiarity with hydrocarbons among technicians and installers, and high cost of R-290 components without the economies of scale, act as barriers. However, the potential for leapfrogging to natural refrigerants (R-290) exists, especially as the sector prepares for the HFC phase-down.

Mobile air conditioning

The MAC sector (cars, buses, trucks) is almost entirely reliant on HFC-134a, with no adoption of natural refrigerants. No significant use of CO_2 or hydrocarbons has been reported in India in this segment, though international trends suggest potential for future adoption as technology and safety standards evolve. Volkswagen has equipped more than 1 million EVs with R-744 heat pump compressors. Mercedes-Benz previously piloted R-744 AC, in combustion engine S-Class and E-Class models for the European market starting in 2017, demonstrating strong performance in high ambient temperature conditions similar to India's. Recently initiatives have been undertaken that aim to demonstrate the commercially viable use of R-290 based secondary loop MAC systems in electric passenger vehicles and light commercial vehicles. This initiative is supported by the Climate and Clean Air Coalition (CCAC) and is implemented by UNIDO in collaboration with Tata Motors.

Challenges: Lack of economies of scale, and the absence of a clear regulatory signal or mandate to drive adoption.

Other applications (heat pumps, transport refrigeration, etc.)

Use of natural refrigerants in heat pumps and transport refrigeration is at a very early stage in India. Some pilot projects and demonstration units using CO_2 and hydrocarbons have been reported, but commercial-scale adoption is limited.

Challenges: Lack of local manufacturing, market awareness, and limited technical know-how; the absence of a GWP or PFAS-based tax.

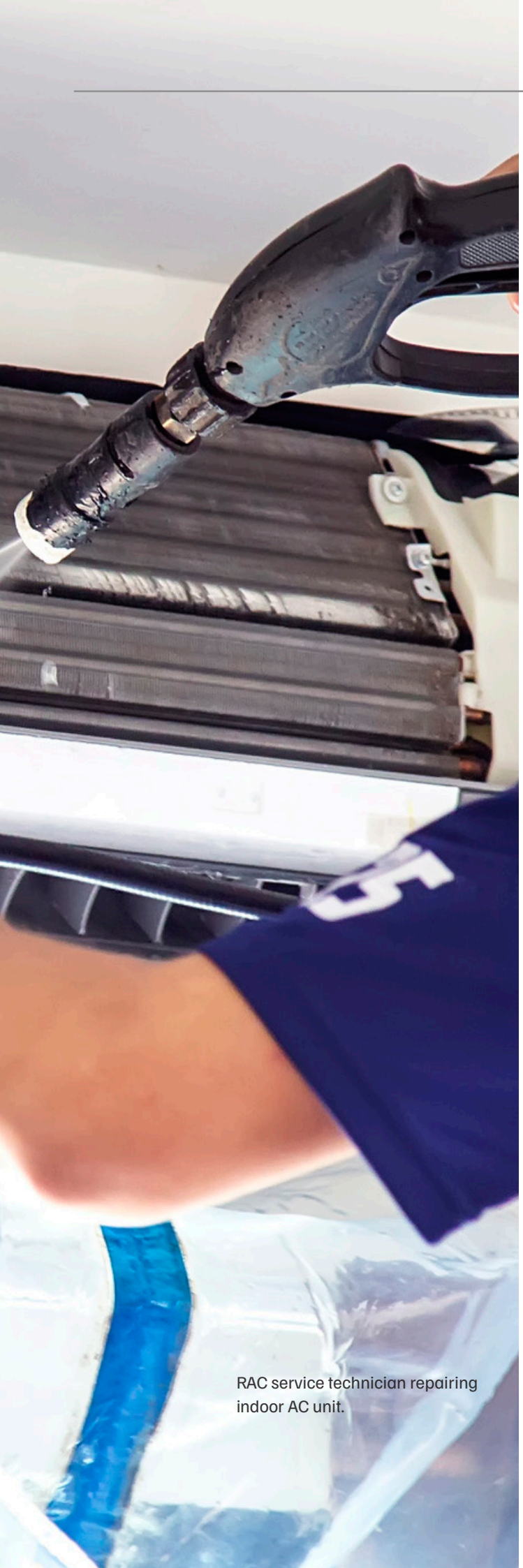
3.2 Global status of natural refrigerant adoption

The global adoption of natural refrigerants is accelerating, driven by regulatory mandates, technological innovation, growing environmental awareness, and the energy savings these systems offer. Recent product launches from leading manufacturers demonstrate significant progress in energy efficiency, safety, and application diversity, from supermarkets and industrial plants to data centres and transportation. Natural refrigerants such as ammonia (R717), carbon dioxide (CO_2/R744), hydrocarbons (propane/R290, isobutane/R600a), and water, are increasingly being adopted as sustainable alternatives to synthetic refrigerants due to their low GWP and zero ODP (ATMOsphere 2024a).

Some of the Non-Article 5 countries, where the HFC phase-down has already started, are spearheading the adoption of natural refrigerants, for example Europe, USA, Canada, Japan, etc. There are multiple factors driving the adoption of natural refrigerants, such as:

- **Regulatory push:** The Kigali Amendment and regional regulations (like the EU's recently revised F-gas Regulation and the US AIM Act) are mandating and accelerating the phase-down (EU–phase-out by 2050) of high-GWP HFCs. These regulations often include GWP limits for specific applications and even outright bans on certain fluorinated refrigerants. These regulations, along with the growing concerns and proposed restrictions on the use of HFOs (PFAS pollution), are creating a strong impetus for natural refrigerant adoption.





RAC service technician repairing indoor AC unit.

- **Enhanced environmental awareness among end-users:** Because of the enhanced awareness of environmental and health issues, and the need for showcasing sustainability/decarbonisation practices, many corporates, businesses, and organisations are preferring natural refrigerant-based systems in their facilities. They demonstrate that defluorination is possible.

- **Energy efficiency performance:** Many natural refrigerant systems can offer comparable or even superior energy efficiency compared to synthetic counterparts, leading to lower operational costs and reduced carbon footprint.

- **Improving cost competitiveness:** While initial investment costs for some natural refrigerant systems might be higher, long-term savings through reduced energy consumption and lower refrigerant replacement costs often make them economically viable. The natural refrigerants market is growing, and is projected to grow significantly in the coming years. This could further help bring the cost down because of economies of scale.

- **Technological advancements and new product offerings:** Continuous innovation in compressor technology, system design, and safety features is overcoming historical limitations associated with natural refrigerants (e.g., high pressures for CO_2, flammability for HCs, toxicity for ammonia). The producers are also gradually expanding their natural refrigerant-based product offering, covering newer applications and demand segments.

As per the market estimates, the number of installations of transcritical CO_2 systems in Europe grew by 33 per cent during 2023 to 2024. In Japan, it grew by 16 per cent during the same period (ATMOsphere 2024b). As the regulations, industry, and markets continue to evolve, natural refrigerants are expected to become the cornerstone of sustainable cooling and heating worldwide, with ongoing developments ensuring their relevance and competitiveness in the years to come.

3.3 Challenges in scaling up natural refrigerants in India

Some of the natural refrigerant technologies are already matured, and widely adopted in some of the demand segments in India, such as domestic refrigerators, and large cold chains. For other sectors, technological solutions exist but are not mainstreamed. The widespread adoption of natural refrigerants in India faces a combination of technical, financial, market, and supply chain-related challenges. The major challenges are discussed below:

- **Technical challenges:** The first set of challenges arises from the properties of some of the natural refrigerants itself. Some of these natural refrigerants pose flammability (hydrocarbons, as for R-32), toxicity (ammonia), and high pressure (carbon dioxide) risks. This requires technical advancements in system design and components, strict safety protocols, and skilled workforce for installation, operation, and maintenance of these systems to ensure safe and smooth operation.

- **Supply chain challenges:** There is a lack of standardised product offering for many of the demand segments or applications. For example, in the case of domestic refrigerators, availability of standard products with certified performance in the market helps in building customer trust and faster adoption. For several applications, such as commercial air conditioning, there is a lack of standard product offering, and the products are custom manufactured as per specific requirements. Also there are limitations in the availability of components such as specialised compressors, high pressure components, safety mechanisms, etc. Additionally, shortage of trained technicians and service personnel competent with natural refrigerant technologies is a significant bottleneck.

- **Market-related challenges:** There is limited awareness about the superior environmental and energy efficiency benefits of natural refrigerants among customers. There are also safety related concerns among the customers regarding flammability and toxicity of some of the natural refrigerants, especially emphasised by the manufacturers of F-gases; however, there is now communication and awareness of the decomposition products like PFAS from F-gases. Because of the custom designed and manufactured products, and limitations in the availability of various components, the lead time from the first enquiry to the final delivery of product significantly increases. This also impacts the customer acquisition cost.

4. Three ways India can make its refrigerant transition sustainable and future-proof

In compliance with its commitment under the Kigali Amendment to the Montreal Protocol, India is developing its strategy for phasing down HFCs. The phase-down schedule for India will start after 2028. This phase of refrigerant transition is primarily driven by concerns about global warming, and the aim is to enable a transition to low-GWP refrigerant alternatives. Broadly two classes of refrigerants have emerged as low-GWP alternatives—HFOs and natural refrigerants.

India's cooling demand, and thus refrigerant demand, is expected to grow multi-fold in the coming years. This increased refrigerant demand will further magnify these issues related to the use of HFOs. Therefore, while HFOs offer a short-term solution to the high-GWP of HFCs, their broader environmental implications are deeply problematic, and raise questions on the long-term sustainability of this transition pathway. There is a risk that PFAS contamination could become so severe that it will lead to the need for another global regulation, and thus new obligations to phase-out the use of HFOs.

The other alternatives that are applied across the globe are natural refrigerants, representing a long-term solution. The technical challenges in the use of natural refrigerants can be addressed through better design and incorporating safety mechanisms in the systems, building technical capacities of engineers and professionals, developing standards and safety protocols, and skill development of technicians. The transition to natural refrigerants will significantly reduce our dependency on IPRs and provide an opportunity for higher indigenisation of future cooling systems.

Thus, while developing the HFC phase-down strategy, a thorough analysis of these factors should be undertaken in consultation with the stakeholders. To summarise, in order to develop a robust strategy and action plan for sustainable and future-proof refrigerant transition, the following factors must be considered:

- **Refrigerant transition involves significant investments and is a resource-intensive process, and thus long-term sustainability of the transition is important.**

  Refrigerant transition requires substantial investments, and resources in upgradation of technologies and manufacturing facilities, development of standards and safety protocols, and training and awareness generation of stakeholders in the supply and demand-side value chain.

- **A comprehensive understanding of the whole lifecycle impact of alternative refrigerants is important in selecting a sustainable transition pathway.**

  The refrigerant transition strategy should **not only be guided by minimising GWP** impacts, but must be balanced with a comprehensive understanding of whole lifecycle impacts of the alternative options, and should carefully weigh-in the trade-offs. This includes evaluating the alternatives on parameters such as climate impacts, chemical persistence and toxicity, other environmental impacts, **human health**, and equitable technological access.

- **Creating a supportive ecosystem for smooth and effective refrigerant transition is necessary.**

  This will involve developing policies and mechanisms for, among other things, (a) providing access to technical and financial assistance to industries and supply chain for upgradation to systems applying natural working fluids; (b) training and certification of the workforce; (c) fast-tracking development of standards and SOPs; and (d) establishing collaboration and synergies among industry, academia, various government agencies, and other relevant stakeholders.

To conclude, there is a negligible possibility of finding/inventing a new refrigerant that is totally safe and environment friendly. The current proposed alternatives in the form of HFOs and their blends present serious environmental and human health issues, in terms of TFA/PFAS contamination. There is a very high cost involved in every refrigerant transition and thus, it is imperative for countries like India to leapfrog to the adoption of natural refrigerants. In addition, and emphasised under the *ICAP*, there should not be reliance only on the vapour compression system for cooling needs, the focus should also be on the deployment of alternative systems, like evaporative and absorption cooling.

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