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How can India Transition to Clean Refrigerants – Learnings from the Global Experiences and Indian Pilots

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1 Introduction

With the commitment to phase down high Global Warming Potential (GWP) refrigerants under the Kigali Amendment to the Montreal Protocol, India is formulating its HFC phasedown strategy to sustainably transition toward low-GWP alternatives. The phasedown schedule for India starts in 2028, with the aim to reduce HFC consumption, in GWP equivalent terms, by 85% of the baseline by 2047 in a phased manner. Refrigerant transition is not new to us. We have witnessed and successfully navigated through a few generations of refrigerant transition. Now we are gearing up for the next phase of refrigerant transition to meet our commitment under the Kigali Amendment to the Montreal Protocol.

This transition in primarily guided by the global warming potential of refrigerant gases, and there are a lot of alternate options available with low GWP. However, there are several other concerns evolving related to impacts of refrigerants on environment, health, and safety in addition to just global warming. The use of hydrofluoroolefins (HFOs), a group of the low-GWP refrigerant alternatives, has initially gained momentum in the developed countries whose phasedown schedule has already started. However, because of the emerging evidences of its adverse impacts on food systems and human health, efforts are now on to restrict the use of HFOs, and transition to natural refrigerants. The natural refrigerants, the other low GWP alternatives, pose flammability, toxicity, or pressure risks, however, with technological advancements in design, operation and maintenance of cooling systems, these risks can be addressed. This provides an opportunity for the developing countries like India (whose phase down schedule is yet to start) to leapfrog to the adoption of natural refrigerants – bypassing the intermediary transition step of HFOs.

1.1 Generations 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, and even water and air. These compounds were chosen primarily for their thermodynamic properties and availability. However, many of these early refrigerants posed significant toxicity, flammability, or pressure risks, raising significant safety concerns that limited their widespread adoption (REHVA 2013).

The search for safer, more stable refrigerants led to the development of synthetic chemicals by the late 1920s, marking the advent of chlorofluorocarbons (CFCs). CFCs were non-flammable, non-toxic, and highly stable, making them ideal for refrigeration, air conditioning, aerosol propellants, foam blowing agents, and solvents. Their inertness, 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 that CFCs were causing significant damage to the stratospheric ozone layer, which protects life on Earth from harmful ultraviolet (UV) radiation. Recognising the urgency of the need to protect 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 recognized as one of the most successful international environmental agreements in history. The Protocol mandates a gradual, stepwise reduction in the production and consumption of ODS, with specific timelines for developed and developing countries (the latter referred to as "Article 5 countries"). This landmark treaty led to the systematic phase-out of ozone-depleting substances (ODS) and has guided the world through a series of refrigerant transitions, each with its own challenges and environmental trade-offs (UNEP Ozone Secretariat).

The initial substitutes of the CFCs were hydrochlorofluorocarbons (HCFCs). HCFCs still have ozone depleting potential, but 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 developed countries completing their phase-out by 2020 and developing countries by 2030.

Refrigerants containing ODSs were replaced by HFCs (hydrofluorocarbons) as a more environmentally-friendly alternative. HFCs do not harm the ozone layer and have become widely used globally. However, they have an exceptionally high global warming potential (GWP) – up to thousands of times higher GWP than CO_2. Due to their ability to raise global temperatures, in 2016, another international agreement – The Kigali Amendment to the Montreal Protocol - came into the picture, under which world leaders agreed to limit 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 developed (85% by 2036) and developing countries (80%-85% by 2045/2047).

Figure 1 illustrates the refrigerant transition journey. Natural refrigerants and hydrofluoroolefins (HFOs) have emerged as the low GWP alternatives that can replace HFCs. Some of the developed countries such as European nations, which initially transitioned to HFOs, are now considering to restrict the use of HFOs and transition to natural refrigerants.

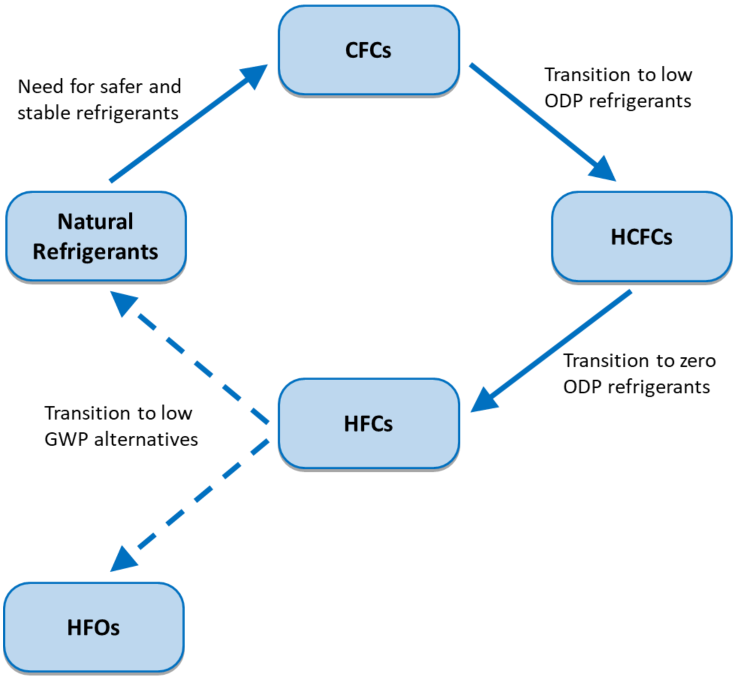

Figure 1: Refrigerant transition journey

1.2 Objectives of this issue brief and Methodology

As India is gearing up for the next phase of refrigerant transition, and is in the process of developing strategy for the same. These refrigerant transitions require substantial investments and efforts in technology upgradation and capacity building of stakeholders in the supply and demand side value chain. Thus, the question is whether it should follow the same path of first transitioning to HFOs and then to natural refrigerants, or it should directly leapfrog to the adoption of natural refrigerants.

The objectives of this issue brief are to:

- Analyse the advantages, suitability, concerns, and issues involved with the adoption of low-GWP alternatives that emerged as replacement of HFCs.
- Initiate the discussion on the right strategy and transition pathway for India, and support development of a sustainable refrigerant transition strategy.

Methodology

The methodology followed for the studies undertaken in the project was ‘mixed method research’ which combines both quantitative and qualitative approaches. The methodology and the steps involved is broadly represented in Figure 2 below. The preliminary finding of this study were also presented and discussed at various forums to gather feedback.

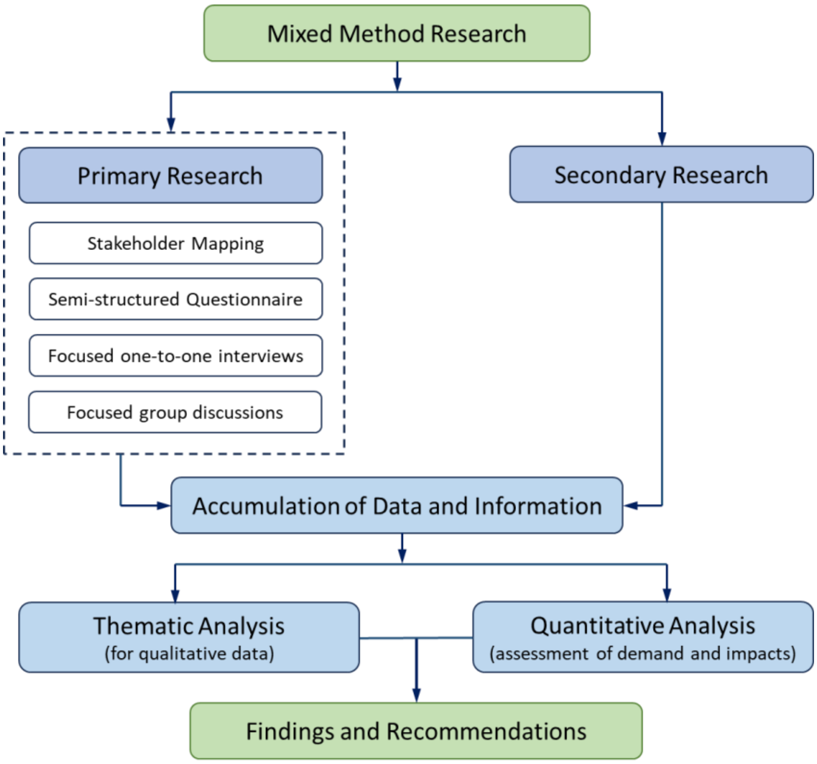

Figure 2: Mixed method research methodology adopted for this issue brief

2 Refrigerant status - market trends, policy drivers, and alternative options

2.1 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 Indian refrigerant market is currently dominated by hydrofluorocarbons, which were initially adopted as replacements for ozone-depleting substances like chlorofluorocarbons and hydrochlorofluorocarbons, in accordance with the Montreal Protocol. However, the high global warming potential of HFCs has prompted a global movement towards phasing them down under the Kigali Amendment to the Montreal Protocol. 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%) 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, R-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 R-22), and a few also use low-GWP alternatives or natural refrigerants, depending on application and cost.
- 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) are using HFO-1234yf, a low-GWP hydrofluoroolefin (HFO).

Table 1: Prevalent refrigerants in various applications and potential low GWP alternatives[1]

Key refrigerant consuming sectors	Current refrigerants in use	Potential alternatives
Room air conditioners	HFC- 32 (677) HFC 410a (1924) HCFC- 22 (1760) HC- 290 (3)	HFC- 32 (677) HC-290 (3) HFC -444B (300) HFC- 454B (466) HC- 290 (3)
Residential refrigerators	HC 600a (3) HFC- 134a (1300)	HC- 600a (3)

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[1] The number in parenthesis denotes the global warming potential of the respective refrigerant gases. IPCC AR 5 (100 years horizon)

Key refrigerant consuming sectors	Current refrigerants in use	Potential alternatives
Commercial (large scale) air conditioning • Ducted Packaged AC • Scroll Chillers • VRF • Screw & Centrifugal Chillers	HFC- 410A (1924) HFC- 407C (1774) HFC- 32 (677) HFC-134a (1300) HCFC-123 (856)	HFC -452B (680) HFC -444B (300) R-454B (466) HC-290 (3) R-717 (NH_3) R-744 (CO_2) (1)
Commercial refrigeration • Display Cabinets • Vaccine /Medical Storage • Cold Storage	HFC-404A (3922) HFC-134a (1300) HC- 600a (3)	HC- 290 (3) HC- 600a (3) HFO-1234yf (<1) R-717 (NH_3) R-744 (CO_2) (1)
Mobile air conditioning	HFC- 407C (1774) HFC 134a (1300)	HFC- 152a (124) HFO-1234yf (<1) HC-290 (3)

(Source: Author's analyses based on stakeholder consultations)

In tandem with its cooling demand, the demand for refrigerants in India is also expected to grow multi fold. The India Cooling Action Plan (MoEFCC 2019) estimates that the annual refrigerant demand will grow 7-8 times by 2037-38 from around 24,300 MT in 2017-18 (Table 2).

Table 2: 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	1,66,000 – 1,81,000

2.2 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:

1. International Agreements (and India's Commitments):

- **The Montreal Protocol on Substances that Deplete the Ozone Layer, 1987** (UNEP Ozone Secretariat)**:**
  - This protocol mandates the phase-out of Ozone Depleting Substances (ODS) like chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (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 significant reductions already achieved (e.g., phase-out of HCFC-141b in foam manufacturing by 2020). This has led to a transition away from R-22, which is still widely used in older ACs but is being phased out with an import ban since 2020 and a full phase-out plan by 2030 (MoEFCC 2024).

- **Kigali Amendment to the Montreal Protocol, 2016** (UNEP Ozone Secretariat)**:**
  - This amendment focuses on the phase down of hydrofluorocarbons (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% cut by 2032, and gradually progressing to cumulative reductions of 20% by 2037, 30% by 2042, and an 85% cut by 2047.
  - This drives the industry towards low Global Warming Potential (GWP) alternatives.

2. 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 licensing 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% to 25%.
    - Reduce refrigerant demand by 25% to 30%, 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% to 40%.
  - While refrigerant agnostic, ICAP promotes "sustainable" and "climate-friendly" choices.

- **Bureau of Energy Efficiency (BEE) Standards and Labelling Program:**
  - 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 efficient and 5-star being the most efficient. The MEPS and criteria for star ratings are periodically revised to ensure periodic improvements in the energy efficiency.
  - Star rating is mandatory for several cooling appliances such as room air conditioners (BEE 2017), refrigerators (BEE 2022), chillers (BEE 2023), and light commercial air conditioners (BEE 2023). This now also include information on refrigerant type and its GWP.
  - This encourages consumers and manufacturers to choose more energy-efficient appliances that utilize climate-friendly refrigerants.

- **Bureau of Indian Standards (BIS) safety standards:**
  - 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 flammable, low-GWP alternatives like R-290 (propane) and R-600a (isobutane).

- **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 room air conditioners are categorized as ‘Electrical & Electronics Waste' under these rules, falling under Extended Producer Responsibility (EPR).
  - Although, these rules do not directly influence the initial refrigerant choices, they indirectly influence as the refrigerant management processes and associated cost that need to be borne by the manufacturers, depends upon the choice of refrigerant

India’s refrigerant choices are primarily influenced by its obligations under the Montreal Protocol and 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.

2.3 The next frontier: low-GWP refrigerants

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:

1. **Natural Refrigerants:** These are substances that occur naturally in the biosphere and have very low GWPs and zero ODPs. Some of the popular examples of natural refrigerants are:
   - Carbon Dioxide (CO_2/R-744): GWP of 1. It is non-flammable and non-toxic, but operates at very high pressures, requiring specialized equipment.
   - Ammonia (NH_3/R-717): GWP of 0. Highly efficient but remains toxic and mildly flammable, primarily used in large industrial applications.
   - Hydrocarbons (e.g., Propane R-290, Isobutane R-600a): GWPs of 3-20. Highly energy-efficient and widely available, but are highly flammable, limiting charge sizes and applications, especially in residential settings.
2. **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 extremely low GWPs (typically less than 10). Examples include R-1234yf and R-1234ze. HFOs are becoming increasingly popular in automotive air conditioning, chillers, and some commercial refrigeration applications. They are mildly flammable (A2L classification).

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.

3 HFOs as a low-GWP alternative – status and concerns

Hydrofluoroolefins (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 (GHG) emissions and comply with international climate agreements like the Kigali Amendment to the Montreal Protocol, HFOs have emerged as a prominent class of low-GWP and zero-ODP refrigerants, promoted as replacements for HFCs and HCFCs in various refrigeration and air conditioning (RAC) applications. The most widely used HFOs today include:

- HFO-1234yf (2,3,3,3-Tetrafluoropropene): Primarily used in mobile air conditioning (MAC) systems as a drop-in replacement for HFC-134a.
- HFO-1234ze(E): Used in stationary air conditioning and refrigeration, as well as in foam blowing and aerosol applications.
- HFO-1233zd(E): Used in centrifugal chillers and foam blowing agents.
- Blends (e.g., R-452A, R-513A, R-449A): These are mixtures of HFOs and HFCs to balance flammability, GWP, and performance.

In addition to low-GWP and zero-ODP, many HFOs and HFO-blends offer comparable or even improved 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 mobile air conditioning (MAC) (EFCTC).

3.1 Concerns with the use of HFOs as refrigerants

Because of these properties, HFOs have emerged as a new generation of refrigerants, however, their adoption has raised significant environmental, health, and regulatory concerns. HFOs are also mildly flammable, but the major issues associated with HFOs are their classification as PFAS, the formation and persistence of trifluoroacetic acid (TFA), the breakdown into super-pollutant R-23, and the implications of patents and intellectual property rights (IPR).

1. The pervasive issue of PFAS and TFAs

One of the most significant environmental concerns surrounding HFOs is their atmospheric breakdown, which leads to the formation of trifluoroacetic acid (TFA) – a short-chain Per- and Polyfluoroalkyl Substances (PFAS). PFAS are a group of synthetic chemicals known for their exceptional persistence in the environment, earning them the moniker "forever chemicals." 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.

HFOs, such as HFO-1234yf and HFO-1234ze(E), break down in the atmosphere to produce 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 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. Globally, refrigerants are responsible for more than 60% 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.

A proposal to restrict the use of per- and polyfluoroalkyl substances (PFAS) was officially submitted to the European Chemicals Agency (ECHA) in January 2023. The proposal aims to significantly curtail the manufacture, use, and placing on the market 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, is currently under extensive review (ECHA 2023). The European Commission is expected to make a final decision on the restriction proposal in 2025. 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 will also have a significant impact on the refrigerant choices worldwide.

2. Breakdown into R-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 R-23 (trifluoromethane), a greenhouse gas with a 100-year GWP of 14,800—far higher than the HFOs themselves. HFO-1234ze(E) was found to generate more than eight times as much R-23 as the other tested HFOs in laboratory conditions. Even if the overall yield is small, the extremely high GWP of R-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. (Michael Garry 2024).

3. Patents and Intellectual Property Rights (IPR)

The commercialization 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 mobile air conditioning (MAC) systems. These patents effectively create a monopoly, limiting the ability of companies in developing countries like India to manufacture or sell HFOs or their blends without licensing agreements. This can stifle competition and innovation, potentially keeping prices high and restricting access to new technologies in developing markets. (CEEW 2016) (C2ES 2016) (DTE 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 broader environmental impacts. Their PFAS classification, degradation into persistent pollutants like TFA and R-23, and the monopolistic control of their intellectual property raise legitimate concerns about the long-term sustainability.

4 Can natural refrigerants be the potential choice for 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 (Global Warming Potential) refrigerants like HFCs and HCFCs.

4.1 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.

1. **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 specialized 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. NH_3 is used in some larger systems. Hydrocarbon-based plug-in cabinets and display cases are being introduced.
   Challenges: Safety concerns, lack of skilled personnel, lack of awareness, and higher upfront costs for advanced systems are key challenges.

2. **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 the 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.

3. **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 extended to Godrej & Boyce Manufacturing Co. Ltd. under India's Hydrochlorofluorocarbon Phase-out Management Plan (HPMP) for the development and commercialization of R-290 (propane) based room air conditioners (RACs). R-290 not only has zero ODP and ultra-low GWP (around 3), but also offers superior thermodynamic performance, however, uptake is limited.

Challenges: The flammability of R-290 poses a significant safety concern, requiring stricter 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 a barrier. However, the potential for leapfrogging to natural refrigerants exists, especially as the sector prepares for the HFC phasedown.

4. **Mobile Air Conditioning (MAC)**

The mobile air conditioning 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 this segment, though international trends suggest potential for future adoption as technology and safety standards evolve. Recently initiatives have been undertaken that aims to demonstrate the commercially viable use of R-290 based secondary loop mobile air conditioning systems in electric passenger vehicles and light commercial vehicles. This initiative is supported by CCAC and is implemented by UNIDO in collaboration with TATA Motors.
Challenges: Stringent safety requirements, lack of suitable technology for Indian conditions, and absence of regulatory push.

5. **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: High costs, lack of local manufacturing, and limited technical know-how.

4.2 Global status of natural refrigerants adoption

The global adoption of natural refrigerants is accelerating, supported by regulatory mandates, technological innovation, and growing environmental awareness. Recent product launches from leading manufacturers demonstrate significant progress in 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 global warming potential (GWP) and zero ozone depletion potential (ATMOsphere 2024).

Some of the developed 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 recent F-Gas Regulation and the US AIM Act) are mandating and accelerating the phase-down 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 restriction on the use of HFOs (PFAS pollution) are creating a strong impetus for natural refrigerant adoption.

- **Enhanced environmental awareness among end-users:** Because of the enhanced awareness on environmental issues and the need for showcasing sustainability/ decarbonisation practices, many corporates, businesses, and organisations are preferring natural refrigerant based systems in their facilities.
- **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 further helps in bringing 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% during 2023 to 2024. In Japan, it grew by 16% during the same period. Figure 3 below highlights the number of installations of transcritical CO_2 systems across major regions in the world. Similarly, the adoption of self-contained hydrocarbon cabinets for refrigeration application is growing rapidly. Figure 4 represents the status of installation of these systems as of December 2024.

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.

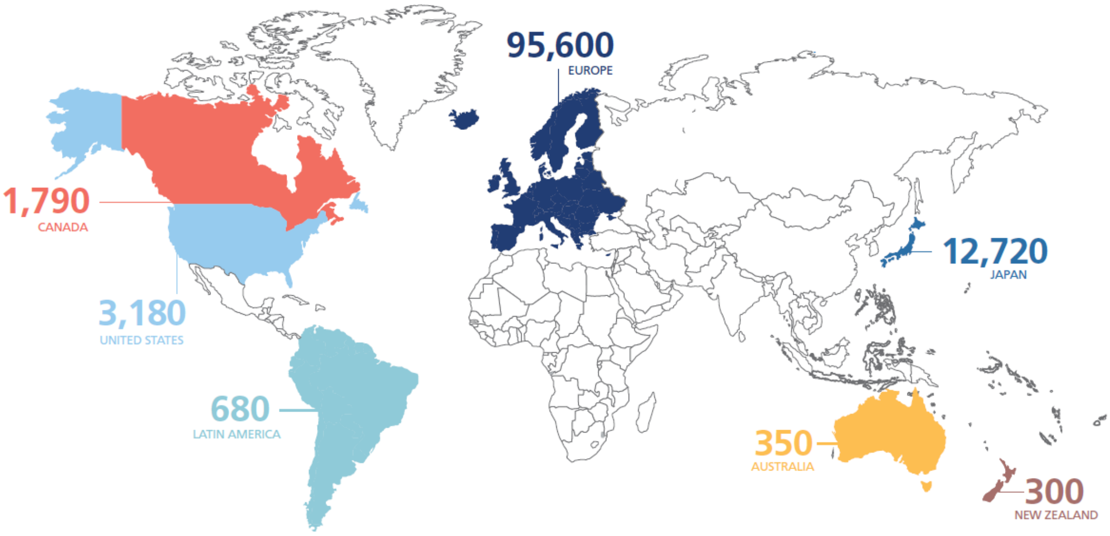

Figure 3: No of installations of transcritical CO_2 systems in major regions as of Dec 2024 (ATMOsphere 2024)

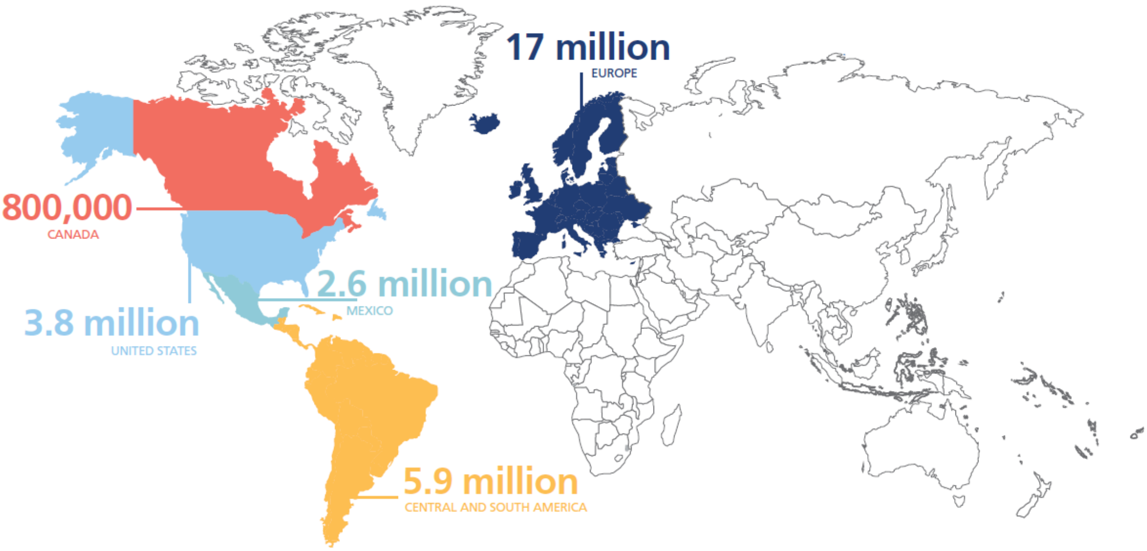

Figure 4: No of self-contained hydrocarbon cabinets installed in major regions as of Dec 2024 (ATMOsphere 2024)

4.3 Challenges in large scale adoption of natural refrigerants in India

Some of 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 arise from the properties of some of the natural refrigerants itself. Some of these natural refrigerants pose flammability (hydrocarbons), 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 lack of standardised product offering for many of the demand segments or applications. For example, in case of domestic refrigerators, availability of standard products with certified performance in the market helps in building customer's trust and their 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 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 environmental and efficiency benefits of natural refrigerants among the customers. There are also safety related concerns among the customers regarding flammability and toxicity of some of the natural refrigerants.

  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.

- **Financial challenges:**

  The initial cost of systems using natural refrigerants is significantly higher in majority of the cases because of multiple reasons – need for specialised components, limited availability and high cost (due to economy of scale) of these components, customised design and manufacturing of products, and longer lead times.

5 Way forward – developing a robust strategy for next phase of refrigerant transition

In compliance with its commitment under the Kigali Amendment of the Montreal Protocol, India is developing its strategy for phasing down of HFC. The phase down schedule for India will start post 2028. This phase of refrigerant transition is primarily driven by the global warming concern, and the aim is to gradually transition to low GWP refrigerant alternatives. Broadly two classes of refrigerants have emerged as low GWP alternatives – hydrofluoroolefins (HFOs) and natural refrigerants.

HFOs are excellent alternatives for their ultra-low GWP, zero ODP, and good energy efficiency performance. However, there are significant concerns regarding their contribution to PFAS pollution, release of R-23 (a super pollutant), and their use restricted by IPRs. India's cooling demand and thus, the refrigerant demand is expected to grow multi-fold in the coming years. This increased refrigerant use 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 raises questions on the long-term sustainability of this transition pathway. It should not lead to a situation where countries are soon negotiating for another phase of refrigerant transition.

The other alternative that emerges are natural refrigerants. There are concerns as well with the use of natural refrigerants related to flammability, toxicity, or high-pressure systems. However, these technical challenges in the use of natural refrigerant 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 technicians. The transition to natural refrigerant will reduce our dependency on IPRs and provide opportunity for higher indigenisation of future colling systems.

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

1. **Refrigerant transition involves huge investments and efforts and thus long-term sustainability of the transition is important.**

   Refrigerant transition requires substantial investments and efforts 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.

2. **A comprehensive understanding of the whole lifecycle impacts of alternative refrigerant 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.

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

This will involve developing policies and mechanisms for, inter alia, (a) providing access to technical and financial assistance to industries and supply chain for upgradation, (b) training and certification of 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.