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**LETTER**

Scenarios for future Indian HFC demand compared to the Kigali Amendment

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Abstract

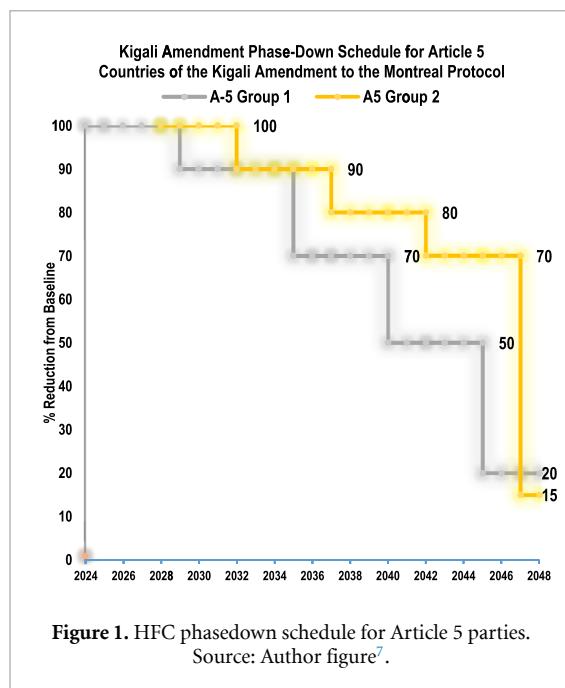
Demand for hydrofluorocarbon (HFC) refrigerants used as substitutes for ozone-depleting substances is growing in India and is estimated to continue growing at a high rate through the middle of this century. HFCs, although not directly ozone-depleting, are highly potent greenhouse gases subject to a global phasedown under the 2016 Kigali Amendment to the Montreal Protocol on Substances that Deplete the Ozone Layer. As of 20 January 2022, 130 Parties have ratified the Kigali Amendment, including India. This analysis evaluates scenarios for India's HFC demand trajectory compared to likely control obligations under the Kigali Amendment. It is based on current and projected markets for HFC-using equipment and types of refrigerants utilized now and likely to be used in the future. Sectors considered in this work include mobile air conditioning, stationary air conditioning, refrigeration, and foam blowing agents. Results suggest that India's annual HFC demand under current market trends could reach 76 MMT CO₂-equivalent (CO₂e) in 2030 and 197 MMT CO₂e in 2050, from 23 MMT CO₂e in 2020, making no changes to the current mix of HFCs in use. The Kigali Amendment requires for compliance that India freeze its HFC consumption in 2028 at a projected level of 59–65 MMT CO₂e and phase down progressively over the following 29 years; in that case, annual Indian HFC demand would peak in 2030 at a projected 57 MMT CO₂e and fall to 8 MMT CO₂e by 2050. This trajectory would avoid cumulative HFC use of 2.2 GT CO₂e through 2050 versus the current market trends. If actions are taken to accelerate the refrigerant transition in stationary air conditioning by five years, India could peak its annual HFC demand by 2028 at 40 MMT CO₂e and avoid additional cumulative HFC demand of 337 MMT CO₂e between 2025 and 2050, exceeding its obligations under the Kigali Amendment.

1. Introduction

Developing countries such as India, Brazil, China, and Indonesia are expected to drive global demand growth for cooling (Sivak 2009, Wolfram *et al* 2012, IEA 2018). The key drivers for this growth are increasing household income, electrification, and an associated increase in appliance ownership. Urbanization and the prevalence of emerging economies located in warm climates made hotter and more humid by

climate change are other notable drivers (Isaac and Van Vuuren 2009, Akpinar-Ferrand and Singh 2010, Challa *et al* 2019, MOEFCC 2019, Sustainable Energy for All 2020).

India currently has the largest unmet cooling demand in the world, but its low adoption rate of air conditioning (8% of the current Indian households have room ACs) and refrigeration equipment is not expected to persist (Davis and Gertler 2015, Khosla *et al* 2021). Projections suggest air conditioner sales



will grow six-fold by 2038, with similar growth in refrigeration (MOEFCC 2019, Khosla *et al* 2021).

This work examines how growing demand for mechanical cooling equipment based on vapor compression will affect uptake and use of chemicals known as refrigerants, which are necessary to produce the ‘cooling effect.’ Chemicals of the same family are also used in the production of insulating foams.

The primary refrigerants and foam blowing agents currently in use, hydrochlorofluorocarbons (HCFCs) and hydrofluorocarbons (HFCs), are subject to global phaseout and phasedown, respectively, under the Montreal Protocol on Substances that Deplete the Ozone Layer (Montreal Protocol). HCFCs contribute to depletion of the stratospheric ozone layer and climate change and HFCs contribute to climate change, although they can also indirectly contribute to modest ozone depletion (Ravishankara *et al* 1994, Hurwitz *et al* 2015). The HCFC phaseout in India has begun in earnest and will largely conclude by 2030 (MOEFCC 2017).

The HFC phasedown in India has yet to begin, but soon will. India signed a global agreement to phasedown HFCs, the 2016 Kigali Amendment to the Montreal Protocol, and ratified it in September 2021 (UNEP 2017, MOEFCC 2021, PMINDIA 2021). The HFC phasedown schedules for parties operating under Article 5 of the Montreal Protocol, which are largely developing countries, is depicted in figure 1. India signed the Kigali Amendment as an Article 5 Group II country, resulting in an obligation to

freeze HFC production and consumption—the latter value being nominally comparable to HFC supply or demand—in 2028 and phasedown in a graduated manner to 15% of the baseline in 2047 (UNEP Ozone Secretariat 2016).

India has relatively low HFC demand today, estimated at 29 kilotons in 2020 and comprised largely of HCFCs, HFCs, hydrocarbons, ammonia, and some hydrofluoroolefins (HFOs)⁸. This usage translates to per-capita rate of 21 grams per person, which is vastly lower than the roughly 430 grams of HFC use alone per person in the United States (US), the country with the highest utilization of refrigerant-based cooling technologies (IEA 2018, US EPA 2021)⁹.

From this modest starting point and facing significant demand growth, India’s refrigerant-using industries will be tasked with reducing the climate impact of HFC refrigerants used in cooling products, as measured under the Kigali Amendment by 100 year global warming potentials (GWPs) calculated by the Intergovernmental Panel on Climate Change in its Fourth Assessment Report (see supplementary table A8 for GWP values). India’s success in achieving widespread access to cooling will depend on its ability to meet all these constraints, including finding climate-friendly refrigerants to meet fast-growing demand.

This analysis assesses multiple scenarios for adoption of alternatives to HFCs and the associated impact on India’s future HFC use trajectory. The analysis then compares the scenarios with likely phasedown compliance obligations for HFC consumption under the Kigali Amendment. It further evaluates the benefit of accelerating the transition to low-GWP refrigerants in stationary air conditioning.

Sectors considered for the analysis include mobile air conditioning (MAC), room air conditioning (RAC), packaged direct expansion systems (DX), variable refrigerant flow systems (VRF), chillers, small and large refrigeration and food cold chain (processing, storage and shipment and marketing), and blowing agents used during production of insulating foams¹⁰.

⁸ This result is approximately consistent with demand estimates outlined in prior work of Kumar *et al* (2018) and the India Cooling Action Plan (ICAP), which projected a total refrigerant demand of 22.2–22.5 kilotons in 2018, excluding foam blowing agents.

⁹ The US per capita HFC use is calculated taking 324 MMTCO₂e HFC use in 2019 (based on EPA 2021 and adjusted for HFC-containing product imports from the U.S. Greenhouse Gas Reporting Program) and assuming an average GWP of 2300 and a population of 318 million people. This figure excludes use on non-HFC refrigerants, which is also substantial.

¹⁰ These sectors cover virtually all potential sources of HFC demand equal to 99% of fluorocarbon use in 2015. Aerosols, fire extinguishers, and solvents at one time used a small amount of HCFCs, but each has non-fluorocarbon alternatives currently being adopted. Any future HFC use in these sectors is expected to be de minimis and thus these sectors are not considered here.

⁷ Based on Article 5 of the Kigali Amendment Treaty Section 8 qua subpart (b) available at <https://ozone.unep.org/treaties/montreal-protocol/articles/article-5-special-situation-developing-countries> (last accessed on July 10, 2021).

2. Methods

The scenario analysis in this paper is built upon a refrigerant and foam blowing agent demand model that estimates the Indian economy's total annual demand for refrigerants and foam blowing agents of all types (i.e. in metric tons, agnostic to chemical types) from 2016 to 2050. The current market assessment is based on the existing literature, India's HCFC Phaseout Management Plan Stage-II (HPMP II), and other available market data (ISHRAE 2015, cBalance Solutions Hub 2016, MOEFCC 2017, Kumar *et al* 2018, Singh *et al* 2019). Building on the current market status, the model forecasts future growth in refrigerant demand based on sector-specific growth rates and, ultimately, saturation levels, employing a 'stock turnover' approach (CalEPA 2016) (see supplementary table A1). The resultant projections are consistent with similar estimates in India's HPMP II, the India Cooling Action Plan (ICAP), and Kumar *et al* (2018)¹¹. As a result of the global COVID-19 pandemic and associated degrowth in several cooling sectors, this work reflects reduced refrigerant demand during 2020 and 2021 which is recovered by 2023, consistent with current industry expectations. The refrigerant demand projection is consistent with the ICAP's intervention scenario for overall refrigerant demand reduction, which would reduce refrigerant demand (on a mass basis) by 25%–30% by 2038 (see supplementary tables A2–A6)¹².

This analysis also estimates India's likely HFC baseline under the Kigali Amendment¹³. One component of this baseline calculation is India's HCFC baseline, which HPMP II provides and may be translated from ozone depletion potential tons to GWP tons (see supplementary table A7). The remaining portion of India's baseline reflects India's HFC consumption averaged from 2024 to 2026, a close approximation of which is provided by the demand projections in this work.

2.1. Refrigerant & foam blowing agent choice scenarios

This work translates annual refrigerant demand (in tons) to HFC demand in CO₂-equivalent (CO₂e) tons by developing two primary refrigerant adoption scenarios: first, the Market Trends scenario, in

Table 1. Refrigerant in use across sectors in Market Trends scenario.

Sector	Substance
Mobile air conditioners (MAC)	HFC-134a
Room air conditioners (RAC)	HFC-32
Packaged direct expansion (DX)	R-410A (50%), HFC-32 (50%)
Variable refrigerant flow (VRF)	R-410A
Chillers	
High pressure	R-410A
Medium/Low pressure	Non-HFCs (e.g. HFOs, R-514A)
Small refrigeration	HFC-134a (70%), hydrocarbons (30%)
Commercial refrigeration	R-404A (70%), HFC-134a (30%)
Cold chain	Ammonia (85%), R-404A (10%), HFC-134a (5%)
Foam blowing agent	HFC-245fa (17%), HFC-365mfc (17%), cyclopentane (66%)

Source: Author assumptions based on industry consultations and literature review.

which HFCs usage patterns reflect today's preferences continuing indefinitely into the future, and second, the Kigali Amendment scenario, in which transitions to lower-GWP alternatives to HFCs are undertaken to implement the Kigali Amendment. An acceleration to part of the Kigali Amendment scenario is also considered.

2.1.1. Market Trends scenario

The Market Trends scenario estimates current adoption trends of HFCs and other refrigerants observed in India based on consultations with local stakeholders, trends in other countries, evaluations in the literature of likely market trends, and changes reflected in official government documents such as HPMP II. This scenario, a type of a 'business-as-usual' case, reflects the direction of the Indian market as of this assessment, and therefore includes a variety of steps taken to reduce reliance on HFCs resulting from the significant global attention afforded to the issue over the last decade, including rapid commercialization and market penetration of next-generation technologies.

The Market Trends scenario assumes no transitions away from HFCs to lower-GWP substances beyond what has already begun. The type of refrigerants and foam blowing agents assumed to be used in each sector indefinitely are shown in table 1.

2.1.2. Kigali Amendment scenario

The Kigali Amendment Scenario assumes that additional steps will be taken to effectuate an economy-wide transition away from HFCs towards

¹¹ This literature contains data on existing and future projected stock of refrigerant-using appliances, growth rates of the segments and other estimates, which formed the basis of the analysis in the paper to arrive at the baseline refrigerant demand projection.

¹² ICAP specifies a target of reduction of refrigerant demand by 25%–30% by year 2037–38 emerging from the interventions proposed in the ICAP and assumed in the 'Intervention Scenario' of cooling demand projections.

¹³ According to the Kigali Amendment, the Article 5 Group II baseline from which reductions are measured is calculated as (all in units of GWP tons): $HFC\ consumption\ baseline = 65\% HCFC\ baseline + average\ HFC\ consumption\ 2024–2026$.

Table 2. Refrigerants in use across sectors in Kigali Amendment scenario with manufacturing transition start and end dates.

Sector	Alternative Refrigerants	Start	End
MAC	Non-HFCs (e.g. HFO-1234yf)	2025	2032
RAC	Non-HFCs	2030	2042
DX	(e.g. HC-290,	2042	2047
VRF	pure HFOs)	2042	2047
Chillers			
High pressure	HFC-32	2030	2040
Medium/Low pressure	Non-HFCs (e.g. HFOs R-514A)	—	—
Small Refrigeration	Non-HFC (e.g. hydrocarbons, HFOs)	2025	2035
Commercial Refrigeration			
R-404A-like	HFC-HFO blends (e.g. R-448A, R-449A)	2024	2029
HFC-134-like	Non-HFC (e.g. HFOs, hydrocarbons, CO ₂ , ammonia)	2030	2050
Cold chain	Ammonia, R-448A, R-449A, HFOs	2027	2037
HFC foam blowing agent	HFOs, cyclopentane	2027	2031

Source: Author assumptions based on industry consultations and literature review.

lower-GWP refrigerants on a timeline that satisfies compliance under the Kigali Amendment, and which is technologically and economically feasible for the Indian industry. These assumptions are shown in table 2. The transition dates in table 2 reflect the timing of industrial conversions from manufacturing products with the current refrigerants to manufacturing them using new, lower-GWP refrigerants. The installed base takes much longer to turn over.

As indicated in table 2, the Kigali Amendment scenario holds that the Indian market will transition away from HFCs in approximately two phases, each with several categories of equipment making the transition.

In the first phase of the transition, starting in the mid- to late-2020s four manufacturing sectors with the greatest technological and economic readiness for lower-GWP alternatives use—MAC using HFC-134a, R-404A-using commercial refrigeration systems, cold chain equipment and small refrigeration systems using HFC-134a, and foam blowing agents—begin transitions to lower-GWP alternatives shown in table 2. In the second phase of the transition, starting in 2030, manufacturing of certain space conditioning equipment—RAC and high-pressure chillers—would begin transitioning away from mid-GWP refrigerants such as HFC-32. The scenario holds that all newly built RAC and

chiller manufacturing capacity brought online starting in 2030 would use low-GWP alternatives, including but not limited to hydrocarbons, HFOs, or a low-GWP HFC options such as HFC-152a¹⁴. Mid-GWP manufacturing capacity already operating in 2030 would be retired only after its useful lifespan. DX and VRF manufacturing capacity would transition later, in the 2040s.

2.1.3. Kigali Amendment scenario with accelerated RAC, DX, VRF Transition

The analysis further explores the impact of advancing the date at which all newly RAC, DX, and VRF manufacturing capacity would begin adopting low-GWP refrigerants, in this case up from the dates shown in table 2 by five years, to 2025, 2037, and 2037, respectively. The feasibility of this acceleration will be evaluated in the *Discussion* section.

3. Results

3.1. Refrigerant demand

India's current HFC demand is approximately 23 MMT CO₂e (figure 2). A majority is comprised of direct stationary space conditioning (RAC, DX, and VRF) and MAC, together accounting for nearly two-thirds of the HFC market on a GWP-weighted basis. The final one-third of the demand is split among chillers, small and large refrigeration, foam blowing agents, and cold chain. The demand estimate shown in figure 2 includes HFCs only and thus does not include any HCFC use remaining in the economy, or any non-fluorocarbons.

India's annual refrigerant and foam blowing agent demand—including all types of substances, not just HFCs—is likely to grow to 185 kilotons by 2050 (figure 3) an increase of almost nine-fold from 2020¹⁵. Growth is dominant in the space cooling sector—which includes RAC, DX, VRF, and chillers—followed by MAC. Even under significant growth assumptions, large refrigeration and cold chain contribute only modestly to overall demand.

3.2. Market Trends scenario

In the absence of Kigali Amendment implementation, India is likely to meet growing refrigerant demand using HFC refrigerants in the sectors that currently use them. The Market Trends scenario results in annual GWP-weighted HFC demand rising from 23 MMT CO₂e today to 76 MMT CO₂e in 2030 and 197

¹⁴ The analysis assumes that no Kigali Amendment-controlled HFCs are used in the low-GWP alternative adopted. If HFC-152a or any other Kigali Amendment controlled substance were to be used, the HFC demand outlook would increase accordingly.

¹⁵ Figure 4 depicts HFC demand, which is the focus of these scenarios but which is only a subset of the total refrigerant demand depicted in figure 3.

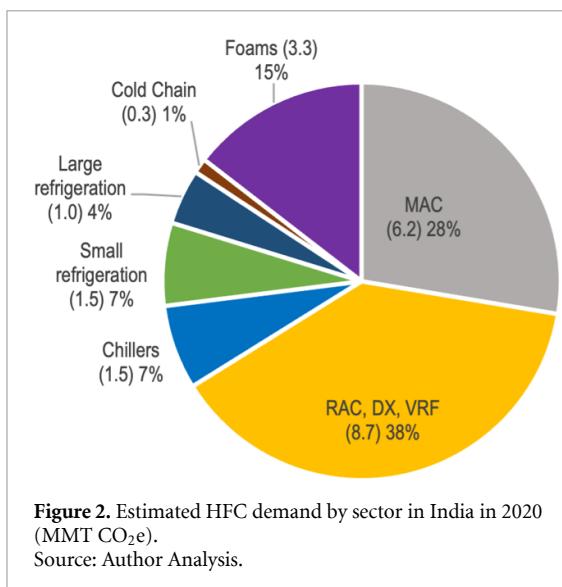


Figure 2. Estimated HFC demand by sector in India in 2020 (MMT CO₂e).
Source: Author Analysis.

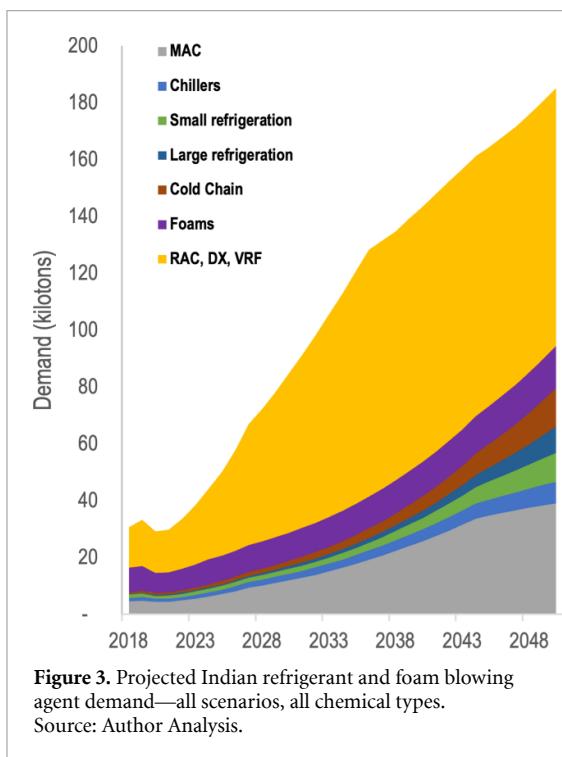


Figure 3. Projected Indian refrigerant and foam blowing agent demand—all scenarios, all chemical types.
Source: Author Analysis.

MMT CO₂e in 2050 (figure 4). As noted in table 1, this scenario reflects the benefits of India's largest sector, RAC, almost entirely adopting mid-GWP HFC-32, a transition that has occurred very rapidly over the last several years, resulting in 90% of RACs using HFC-32 in 2022. A much smaller subset of smaller RACs utilizing hydrocarbon R-290, while DX and VRF utilize R-410A. In the absence of Indian industry's adoption of HFC-32, India's HFC growth trajectory would be much higher, as R-410A's 100 year GWP is more than three times greater than that of HFC-32.

Figure 4 shows results for the Market Trends scenario as well as the Kigali Amendment control schedule

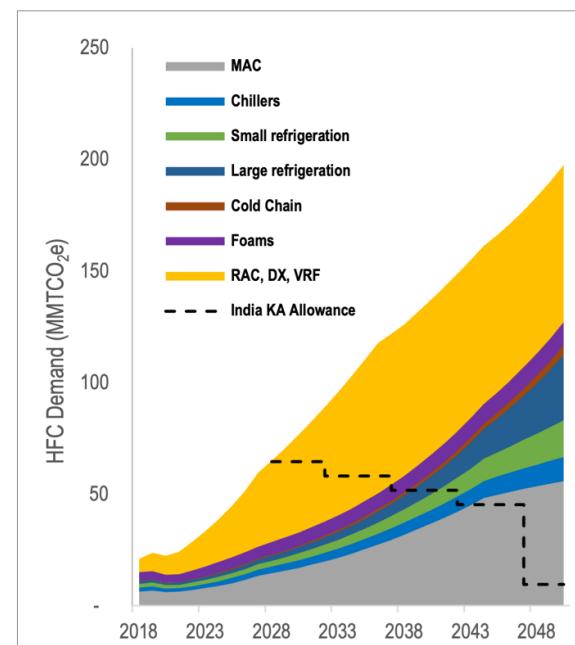


Figure 4. Projected HFC demand for Market Trends scenario—all sectors.
Source: Author Analysis.

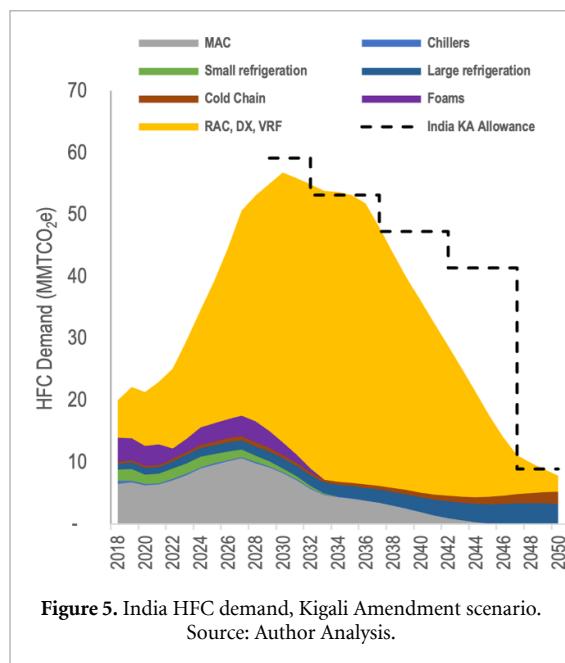
projected for India. India's baseline HFC consumption for Kigali Amendment limits (i.e. the phasedown starting point) is projected to be 65 MMT CO₂e if it takes no action prior to 2027 to abate HFC use, as in this scenario¹⁶. India's HFC demand will surpass its baseline allocation promptly in 2028, the year control measures begin, and vastly exceed it in the years and decades to follow.

3.3. Kigali Amendment scenario

The Kigali Amendment scenario, with transitions outlined in table 2, results in significant HFC demand reductions from the Market Trends case. Annual HFC consumption peaks in 2030 at 57 MMT CO₂e and falls to about 8 MMT CO₂e by 2050, as shown in figure 5. The pace of HFC demand reductions is somewhat gradual in the early 2030s but accelerates later in that decade in anticipation of the significant 2047 reduction step.

HFC demand in the MAC sector plateaus beginning around 2025 as the manufacturing sector begins transitioning to low- GWP alternatives, a process that is completed in 2032, but a modest service demand tail continues to taper off until about 2045. HFC demand from large refrigeration and cold chain

¹⁶ India's baseline changes between the two scenarios due to early action to mitigate HFC demand in the *Kigali Amendment* scenario. Because India's Kigali Amendment baseline is determined based on HFC consumption levels between 2024 and 2026, India's baseline will decrease if it takes action to reduce HFC demand prior to the start of 2027. This analysis projects a 59 MMTCO₂e baseline in the *Kigali Amendment* scenario, which assumes India takes such early action to curtail HFC demand, compared to 65 MMTCO₂e in the *Market Trends* case, in which India does not. The baseline falls further, to 56 MMTCO₂e, in the accelerated RAC, DX, VRF scenario.

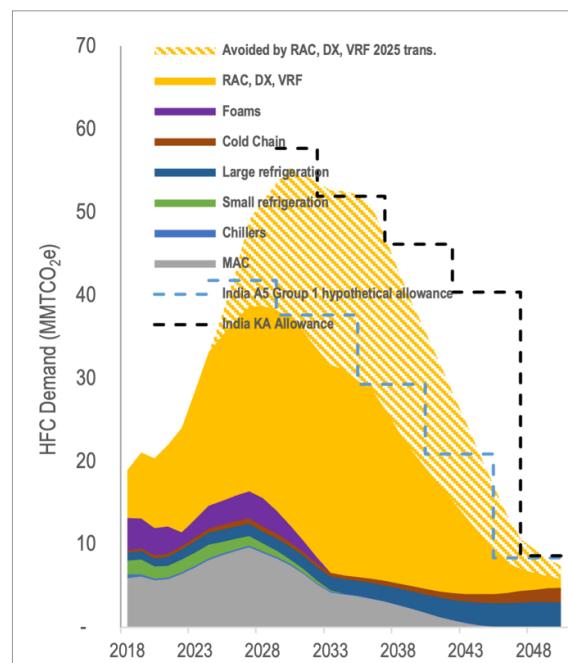


systems—not assumed to transition to low-GWP, but simply assumed to eliminate very-high-GWP substances—persists as the sector grows, ultimately becoming a significant source of residual HFC demand by mid-century. As noted in the *Discussion* section, there is significant uncertainty in the future market preferences for equipment in this sector and thus also in this result.

RAC, DX, and VRF dominate overall HFC demand. Strong growth in this sector alone accounts for nearly all the economy-wide growth in HFC demand until 2030, at which point newly-built RAC, DX, and VRF manufacturing capacity is projected to begin adopting low-GWP alternatives (i.e. there is no additional new HFC-32 based manufacturing capacity added after 2030).

Economy-wide demand reductions in the 2030s are driven largely by reductions from the other sectors, primarily MAC and small refrigeration, while demand reductions attributable to RAC, DX, and VRF increase as 2040 approaches due to growing retirements of by-then legacy HFC-32-based manufacturing lines retiring. HFC demand from large refrigeration and cold chain equipment grows only slightly over the coming decades in this scenario, reflecting a balance between growth in absolute terms and adoption of lower-GWP refrigerants. HFC use in foam blowing agents also diminishes quickly following the HFC freeze date, phasing out completely around 2033.

Taken together, these steps satisfactorily maintain Indian HFC demand approximately at or below the required cap on HFC consumption under the Kigali Amendment throughout the 29 year phasedown. This trajectory would avoid cumulative HFC use of 2.1 GT CO₂e through 2050 versus the Market Trends scenario.



3.4. Kigali Amendment scenario with accelerated RAC, DX, VRF transition

Because of the predominance of space cooling, advancing the date at which all newly built manufacturing capacity of RAC, DX, and VRF begins adopting low-GWP alternatives may be an attractive approach to accelerate the overall transition away from HFCs. Advancing that date from 2030 to 2025 for RAC, by far the biggest subsector of the three, and to 2037 for the remaining two, would result in major reductions to the overall HFC demand projection, as shown in figure 6.

Under this scenario, India's annual HFC demand approximately peaks at 40 MMT CO₂e in 2028, with growth tapering rapidly after 2025 until reductions begin in 2030. The cumulative avoided HFC demand is significant—in total 337 MMT CO₂e between 2025 and 2050 compared to the Kigali Amendment scenario—and brings India's HFC trajectory handily under what would be permissible should it elect to accelerate its HFC phasedown schedule to follow the schedule for Article 5 Group I countries.

Figure 7 summarizes the change in HFC demand trajectory among the three scenarios.

4. Discussion

The Kigali Amendment scenario illustrates one potential path for an Indian HFC phasedown that complies with the current projected Kigali Amendment control schedule for India. Although there may be several combinations of interventions that would yield similar results, the high fraction of total demand

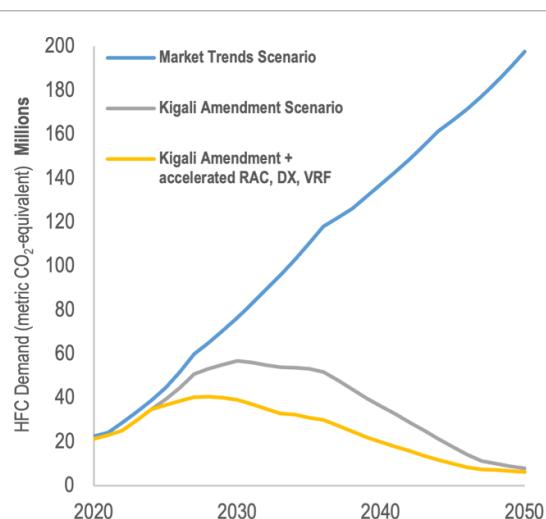


Figure 7. HFC demand scenarios (market trends, Kigali Amendment, and Kigali Amendment plus accelerated RAC, DX, VRF) compared to Kigali Amendment.
Source: Author Analysis.

attributable to space cooling and MAC suggests that any national implementation of the Kigali Amendment will be required to achieve at least this pace of reductions in these critical sectors. It is also important to evaluate the technological and economic feasibility, and best timing, of each constituent step for the Indian context.

The MAC sector has been first to transition in many economies that have begun reducing HFC use, including the US and EU (EU 2006, US EPA 2015). HFO-1234yf is technologically and economically feasible and implemented widely around the world (TEAP 2019). India further has domestic production of HFO-1234yf (CEEW, IGSD, NRDC and Seidel and Ethridge 2016). Currently, HFO-1234yf is patented and subject to joint marketing agreements, limiting HFO-1234yf production to licensed uses, but application patents will expire sometime between 2024 and 2026 (Seidel and Ye 2015, Bhushan 2016, Sherry *et al* 2016). Considerable work has also been done to demonstrate the feasibility of HFC-152a-based secondary loop MACs in India (Andersen *et al* 2013, CEEW, IGSD, NRDC and C2ES 2016, Kapoor *et al* 2017, Craig *et al* 2020).

India's motor vehicle industry today is globalized, and manufacturers are already exporting vehicles fitted with HFO-1234yf AC systems to countries that require low-GWP refrigerants. This and other global market forces, including those related to refrigerant and component supply, may encourage faster adoption of low-GWP substances than would otherwise occur during Kigali Amendment implementation.

Refrigeration installations using R-404A, with its extremely high GWP of 3,922, were among the first end-uses targeted for regulation in the EU under its F-gas Regulation and by US EPA under Significant New Alternatives Policy Program HFC prohibitions

(EU 2014, US EPA 2015). Like-for-like replacement of R-404A can be achieved with HFC-HFO blends R-448A or R-449A (Honeywell 2015, Makhnatch *et al* 2017). Alternatively, products such as remote condensing units can temporarily use HFC-134a, which has one-third the GWP of R-404A, as a significant fraction of them currently do (Kumar *et al* 2018). Smaller refrigeration units are transitioning globally to hydrocarbon refrigerants, which is largely feasible due to the modest charge sizes and self-contained nature of these products, and in fact is preferable for the energy efficiency and acoustic advantage of hydrocarbons (Bjorn 2008, Booten *et al* 2020).

The RAC, DX, and VRF sector is by far the biggest contributor to India's overall HFC demand. Rapidly growing use of HFC-32—accounting for a current total of 90% of the RAC market, according to industry consultations conducted for this work—is a significant success for India and has avoided a large buildup of R-410A-based manufacturing. The Market Trends scenario makes it clear, however, that HFC-32's GWP of 675 makes HFC-32 almost certainly untenable as a long-term solution for India given its low HFC baseline and high growth potential.

As such, identification and adoption of a suitable low-GWP alternative is of paramount importance. In the case of room ACs up to and including 1.5 tons, low-GWP alternative R-290 is already being used and accounts for about 2% of annual sales, a rate that has not grown significantly in the nearly 10 years R-290-based models have been on the market (NRDC, IGSD and TERI, 2018 and Green Cooling Initiative). Issues of flammability are widely believed to limit more widespread adoption at this time, although work is ongoing in India to develop additional safety standards to facilitate broader use of hydrocarbon refrigerants.

In 2021 the Global Cooling Prize, a contest to develop an 80% less climate-impactful air conditioner led by the Rocky Mountain Institute and the Government of India, resulted in two winning air conditioners that utilized low-GWP refrigerants HFO-1234ze and HFC-152a, respectively (Kalanki *et al* 2021). These refrigerants have different thermodynamic characteristics compared to commonly-used refrigerants—most notably, they have significantly lower operating pressures than, say, R-410A or HFC-32—and thus major system redesigns may be needed to incorporate them.

Advancing the low-GWP transition for RAC, DX, and VRF is the highest-impact way to expedite the HFC phasedown in India. Advancing the start of the RAC transition to 2025 in particular would likely also have a financial benefit; according to decisions of the parties to the Montreal Protocol, new HFC-based manufacturing capacity added after 2024 (or 2025 if converting existing capacity to HFCs without Multilateral Fund support) will generally not be eligible for

Multilateral Fund assistance to replace the HFCs later (UNEP Ozone Secretariat 2016b)^{17,18}. Nonetheless, transitioning this sector early may prove technologically or economically challenging due to difficulties with incorporating newer, low-GWP fluids into existing equipment designs and the relative newness and upfront cost of technologies debuted for the Global Cooling Prize.

In general, the Kigali Amendment scenario suggests that beginning the overall transition away from high GWP-HFCs any later than the mid-2020s will result in a large installed stock of HFC-based units, requiring stronger and more aggressive transition efforts in the latter part of the transition timeline for India. Such a scenario may result in a need for manufacturing sectors to transition faster than they have in the past, for example, or may result in insufficient quantities of HFCs available to service existing products for the entirety of their useful lives, which may be economically harmful. Near-term policy and investment project planning will benefit industry, consumers, and the environment.

An additional factor to consider in India's HFC phasedown is commercial and cold chain refrigeration systems. Currently, India has very few supermarket-style food retail establishments, a sector responsible for more than one quarter of US HFC demand, for example (US EPA 2021). Some estimates suggest that supermarkets and hypermarkets are expected to grow dramatically in popularity through mid-century, driven by rising urbanization rate and transition from informal establishments to a more formal business and supply chain (Sharma *et al* 2017).

However, smaller, neighbourhood market-style establishments have been favoured to date in India and may continue to be. With the future of the mix of food retail settings still unclear in India, the mix of low-GWP refrigerants available to meet refrigeration needs is naturally still unclear. Continued use of smaller, more decentralized refrigeration units will more readily enable use of low-GWP refrigerant alternatives, while widespread adoption of large, distributed supermarket-style compressor rack systems presents greater challenges for refrigerant choice and leak management.

Although not considered in the analysis here, better installation and service practices, plus refrigerant reclamation at end of life, can also play a significant role in reducing HFC demand. Proper installation and servicing help avoid system leaks, which reduces need to top up refrigerant during servicing and thus reduces overall refrigerant demand. Refrigerant reclamation at end of life avoids sending used refrigerant into the waste stream—either a destruction facility or, worse, the atmosphere—and creates a new supply of refrigerant that does not count against Kigali Amendment limits. Scaling up these practices will provide significant additional flexibility in the HFC phasedown.

In addition, a major co-benefit of the Montreal Protocol has been improved energy efficiency. Transitions to new refrigerants have historically sparked innovation and upgrades to aging designs and components, for example, which present an opportunity to improve equipment energy efficiency (IEA 2018, UNEP and IEA 2020). Lower-GWP refrigerants also generally provide higher efficiency and cooling capacity compared to conventional HFCs (Abdelaziz *et al* 2015, Shah *et al* 2019). It is therefore likely that greater CO₂e emissions reduction gains can be achieved if prioritizing energy efficiency gains during refrigerant transition (Park *et al* 2021). The analysis in the paper does not include equipment energy efficiency considerations because it does not directly impact HFC demand.

5. Limitations

This work presents 'if-then' results that quantitatively follow from the set of modelled input parameters described in this paper. It is not a prediction of the future; rather, it sheds light on the impact of various policy and technology investment decisions that may be considered and undertaken in the coming years.

This work does not project HFC 'emissions'; rather, its focus is on 'demand.' HFC demand and emissions are not the same quantities but should be aligned to an extent. India does not currently report HFC emissions (other than HFC-23, a by-product of HCFC-22 production), and there is limited information available regarding India's current rate of HFC emissions.

The sole atmospheric observation-based estimate of Indian HFC emissions, Say *et al* (2019), reports results of aircraft-based halocarbon measurements over India in 2016 and found very high overall implied HFC emissions. These measurements imply HFC-125 emissions levels far in excess of the sum of emissions of HFC-32 and HFC-143a, two substances commonly blended evenly with HFC-125 for use in refrigeration and air conditioning, an explanation for which this work does not find. This result also does not explain the full extent of Say *et al*'s measured HFC-134a emissions, which are also higher than expected.

¹⁷ The Multilateral Fund for the implementation of the Montreal Protocol is the financial arm that implements the Montreal Protocol. The main objective of the Fund is to assist developing country parties to the Montreal Protocol whose annual level of consumption of the ODS, chlorofluorocarbons (CFCs) and halons were less than 0.3 kilograms per capita in (1990) to comply with the control measures of the Protocol. 147 of the 197 Parties to the Montreal Protocol meet these criteria. They are referred to as Article 5 countries.

¹⁸ Enterprises may receive funding to replace HFC-based manufacturing capacity added after the 2024/2025 date with Multilateral Fund support, 'if necessary to meet the final HFC phase-down step; if there were 'no other alternatives... available' at the time the HFC-based manufacturing capacity was added.'

Say *et al* notes, and we can confirm, that the 2016 measurements of HFC abundances indeed imply a significant disagreement between the mainstream literature's, including this work's, understanding of the size and makeup of the Indian HFC market and atmospheric measurements. Additional atmospheric monitoring and bottom-up HFC inventorying are warranted to better understand these discrepancies and India's HFC market more generally in advance of Kigali Amendment implementation.

6. Conclusion

India's current demand for HFCs is low, due in part to the low overall penetration of cooling appliances and preference for non-HFCs and comparatively lower-GWP HFCs in the phaseout of ozone-depleting substances. As such, and particularly considering the very high temperatures within the country and the need to advance access to cooling technologies, the market for refrigerant-based cooling products has significant growth potential in the coming decades. That period will coincide with reducing reliance on HFCs under the Kigali Amendment to the Montreal Protocol, encouraging timely choices to be made about refrigerants used in the manufacture of cooling appliances in the near future.

A handful of strategic transitions to climate-friendly alternatives, beginning in the mid-2020s and redoubling in the 2030s, and largely reliant on technologies known and commercialized today, is sufficient to set India on a track that would peak and reduce its HFC demand in line with the Kigali Amendment. Delaying any intervention to after India's 2028 freeze on HFC consumption will result in the need to make much faster reductions than would otherwise be necessary. As preparations are made to implement the Kigali Amendment, including a national HFC phasedown strategy planned for 2023, the Indian government and industry have the opportunity to decide on interventions beginning by the middle of this decade to head off significant potential growth in HFCs in such a way that the Indian market for cooling appliances can continue to grow unconstrained.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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