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Scenario Analysis for HFC Emissions in India: Mitigation potential and costs

Pallav Purohit ■ Lena Höglund-Isaksson ■ Imrich Bertok ■ Vaibhav Chaturvedi ■ Mohit Sharma

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CEEW's major projects on climate, environment and resource security include advising and contributing to climate negotiations (COP-21) in Paris; assessing global climate risks; assessing India's adaptation gap; low-carbon rural development; environmental clearances; modelling HFC emissions; business case for phasing down HFCs; assessing India's critical mineral resources; geoengineering governance; climate finance; nuclear power and low-carbon pathways; electric rail transport; monitoring air quality; business case for energy efficiency and emissions reductions; India's first report on global governance, submitted to the National Security Adviser; foreign policy implications for resource security; India's power sector reforms; resource nexus, and strategic industries and technologies for India's National Security Advisory Board; Maharashtra-Guangdong partnership on sustainability; and building Sustainable Cities.

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His research is focused on Indian and global energy and climate change mitigation policy issues- carbon dioxide emission stabilization pathways, low carbon and sustainable energy policies, modelling energy demand, and water-energy nexus within the integrated assessment modelling framework of the Global Change Assessment Model (GCAM). Vaibhav's recent work includes analyzing nuclear energy scenarios for India, Indian HFC emission scenarios, climate policy-agriculture water interactions, transportation energy scenarios, model evaluation, investment implications for the global electricity sector, and modelling the building sector energy demand scenarios for India. Vaibhav has been actively involved in global model comparison exercises like Asian Modelling Exercise (AME) and Energy Modelling Forum (EMF).

At CEEW, Vaibhav's research focuses on India within the domain of energy and climate policy, mid-range and long-range energy scenarios, HFC emission scenarios, urban energy demand pathways, and energy-water inter relationship. He has been actively publishing in leading international energy and climate policy journals.

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Mohit Sharma is a Junior Research Associate at the Council on Energy, Environment and Water (CEEW). His research interests include sustainable energy, climate research and improvements in urban ecosystem. He has developed the bottom up Hydrofluorocarbon-HFC emissions module for modelling long term HFC emissions. His focus area of work at CEEW is urban sustainability and addressing the urban challenges through an integrated approach. He also shares his knowledge on energy systems' modelling and optimisation for developing energy modelling capabilities at CEEW.

Mohit graduated from Technical University of Denmark-DTU with two years' Master in Sustainable Energy. A major part of his master's programme, he spent learning and solving practical problems, at DTU-Risø National Laboratory for Sustainable Energy. He has worked as Research Assistant with DTU and on other short-term research projects with Danish industry. During this period, he worked on thermodynamic modelling of transcritical CO_2 system for cooling applications, life cycle assessment of products and feasibility of solar-thermal driven cooling cycle for residential applications.

Prior to his post graduation, he has close to two years of work experience in process industry including project management for new process plants and operational optimisation for industrial processes. Mohit holds a degree in Chemical Engineering from National Institute of Technology. Before joining CEEW, Mohit briefly volunteered with CSE to prepare framework for national energy modelling.

Contents

List of Acronyms and Abbreviations

AR4	Fourth Assessment Report of the IPCC
CCAC	Climate and Clean Air Coalition
CDM	Clean Development Mechanism
CEEW	Council on Energy, Environment and Water
CFC	Chlorofluorocarbon
CO_2	Carbon Dioxide
CH_4	Methane
CLE	Current Legislation
EU	European Union
GAINS	Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS)
GCAM	Global Change Assessment Model
GHG	Greenhouse Gas
GOI	Government of India
GWP	Global Warming Potential
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
IIASA	International Institute for Applied Systems Analysis
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
ISHRAE	Indian Society of Heating, Refrigerating & Air Conditioning Engineers
MC	Marginal Cost
MEA	Multilateral Environment Agreement
MFR	Maximum Feasible Reduction
MLF	Multilateral Fund
MoEF	Ministry of Environment and Forest
MoEFCC	Ministry of Environment, Forest and Climate Change
MP	Montreal Protocol
N_2O	Nitrous Oxide
ODS	Ozone-Depleting Substance
PFC	Perfluorocarbon
RAMA	Refrigeration and Air-Conditioning Manufacturers' Association
SF_6	Sulphur Hexafluoride
SIDS	Small Island Developing States
TEAP	Technology and Economic Assessment Panel
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency

Executive Summary

Hydrofluorocarbons (HFCs) are often used as substitutes for ozone-depleting substances (ODSs) in various sectors, including refrigeration, air-conditioning, aerosols, fire extinguishers, and foam blowing. In addition, HFC-23 is generated as a by-product of chlorodifluoromethane (HCFC-22) production for feedstock use in industry and for emissive use. HFCs are the fastest-growing group of greenhouse gases in much of the world, increasing at a rate of 10–15 percent per year. At present, India is following the Hydrochlorofluorocarbon Phaseout Management Plan (HPMP) as part of its international commitment under the Montreal Protocol to mitigate consumption of ODSs. This transition is almost complete in non-Article 5 parties (primarily developed countries). However, the phase-out of hydrochlorofluorocarbons (HCFCs) has largely resulted in a transition towards hydrofluorocarbons (HFCs), which are potent greenhouse gases. In India, the majority of refrigeration and air-conditioning systems produced and marketed currently use HCFC-22. The impending transition away from HCFCs would in all probability lead to the higher consumption and emission of HFCs in India.

If India moves towards HFCs across sectors, there will be a significant increase in the emissions of HFCs. However, the pace and magnitude of these emissions, as well as the economy-wide mitigation cost of mitigating potential HFC emissions, are not well understood. The Council on Energy, Environment and Water (CEEW) along with the International Institute for Applied Systems Analysis (IIASA) has initiated joint research to address this research gap. The study is aimed at understanding the following questions:

a. What will be the global warming impact of high-GWP HFC emissions from the refrigeration (commercial, domestic, industrial, transport), air-conditioning (stationary and mobile), and industrial (aerosols, foams, solvents, etc.) sectors in India under the reference scenario?

b. What is the maximum feasible reduction possible across HFC emission sectors based on the advanced control technologies/options (ACT) available globally and what is the cost-optimal strategy for the same? Can India leapfrog high-GWP HFCs immediately?

c. What are the implications of a global agreement on HFCs as per the proposed Montreal Protocol amendments?

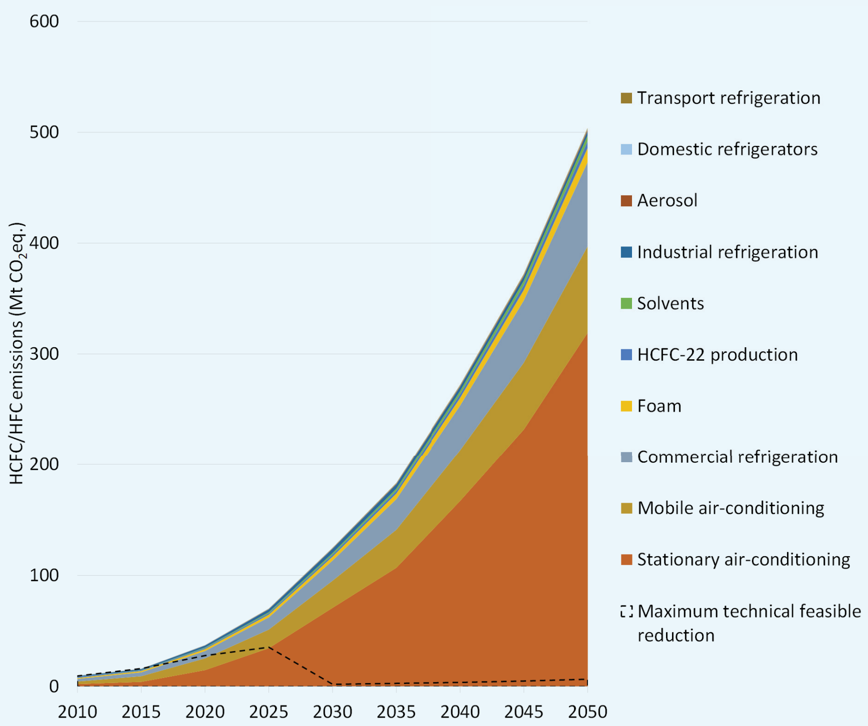
The first phase of the research focused on developing the current legislation or reference scenario for understanding the magnitude of HFC emissions across sectors until 2050 (Chaturvedi et al., 2015)[1] using the integrated assessment modelling framework of Global Change Assessment Model (GCAM). This second phase of the research focuses on the next set of questions. This study presents estimates of current and future HFC emissions in India along with their technical mitigation potential and associated costs for the period 2010 to 2050. The analysis uses the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model framework developed by IIASA to estimate emissions, mitigation potentials, and costs for all major sources of HFC emissions for 23 states/regions, as shown in Appendix I, which are aggregated to produce national estimates. The intellectual approach adopted for understanding the mitigation costs for the HFC phase-down is grounded in the methodology used in climate-policy research. As per this approach, emission mitigation potential is estimated in reference to a 'business-as-usual' scenario, and economy-wide mitigation costs are calculated corresponding to the economy-wide mitigation potential under each alternative policy scenario. The cost-calculation methodology is different from the way in which costs are calculated under the Multilateral Fund (MLF) of the Montreal Protocol. The objective of MLF is to support industries in Article 5 parties (primarily developing countries) for transitioning away from

1 Available at http://ceew.in/pdf/ceew-indias-long-term-hydrofluorocarbon-emissions-29-may-15.pdf

high-GWP HFCs. Given this objective, MLF compensates for the loss of profit (or the incremental cost) for industries or companies that will be impacted by a phase-down. The approach taken by this study, on the other hand, estimates the economy-wide costs of a transition, irrespective of who within the economy will bear this cost.

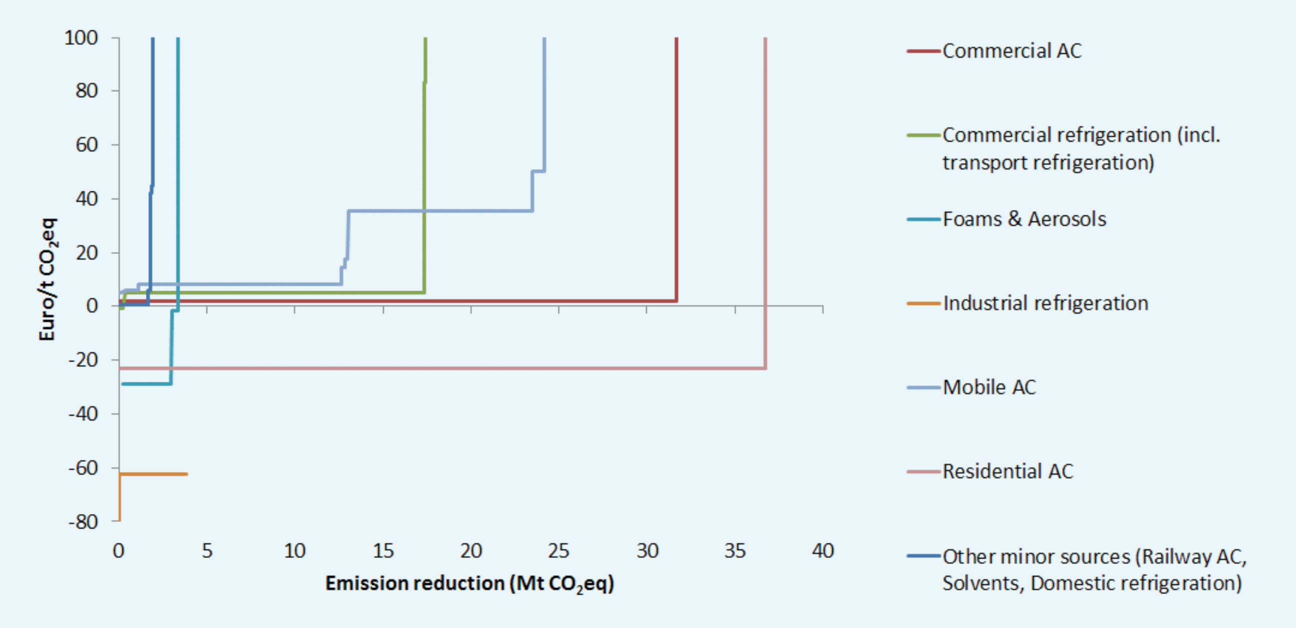
For each region, ten emission-source sectors with mitigation potentials and costs were identified for HFCs. HCFC/HFC emissions are estimated at 10 Mt CO_2eq in 2010 with an expected increase to about 503 Mt CO_2eq in 2050. The growth is estimated to be caused mainly by the increase in HFC emissions from refrigeration and air-conditioning applications. Further, the increase in HFC, in turn, represents the combined effect of the replacement of HCFCs with HFCs in accordance with the revised Montreal Protocol and the expected increase in demand for refrigeration and air-conditioning.

Figure 1: Sectoral development of baseline HCFC/HFC emissions 2010–2050



There are extensive opportunities to reduce HFC emissions by up to 98 percent primarily through replacement with existing alternative low-GWP substances. The results indicate that approximately 37 percent of the mitigation potential is attainable at zero cost, while nearly 90 percent reduction is attainable at a cost of less than 20 €/t CO_2eq due to the low cost of alternative refrigerants (particularly in case of HCs) as compared to HFCs. The mitigation potential is high and inexpensive for the residential air-conditioning, industrial refrigeration, and foam sectors due to the availability of less expensive alternatives (HCs, NH_3, HFC-152a, etc.) as compared to HFCs. For commercial air-conditioning, domestic refrigerators, and commercial refrigeration, the mitigation potential is high and relatively inexpensive as compared to mobile air-conditioning.

Figure 2: Marginal mitigation cost curve for maximum technical reduction of HFC emissions in India in 2030 by sector



In the current legislation or baseline scenario for India, cumulative HFC emissions are estimated at 6.8 Gt CO_2eq[2] in the period 2015 to 2050. The maximum technically feasible mitigation potential is estimated at 6.4 Gt CO_2eq for the same period. At present, proposals have been submitted by North America (NA), the European Union (EU), Small Island Developing States (SIDS), and India to amend the Montreal Protocol to substantially reduce growth in HFC use. The scenario analysis indicates that approximately 6.1 Gt CO_2eq cumulative HFC emissions reduction is possible following the NA, EU, and SIDS proposals in the period 2015 to 2050. The reduction in cumulative emissions is less for the Indian proposal (4.2 Gt CO_2eq) because of the later start of the controls for developing countries than in the other proposals.

In this study, we have incorporated the incremental cost of transitioning to low-GWP or natural alternatives and cost implications of energy efficiency as well. However, the transaction costs, e.g., for the special training of technicians and for the installation of new safety routines when these are needed, are not considered in this study. The mitigation potential attainable at a zero or negative marginal cost is expected to be cost-effective and therefore to occur spontaneously when policy measures are taken to address the initial transaction costs mentioned above. As different sectors will face different costs, we present both positive and negative costs separately for different proposals.

Due to the different freeze-in years and baselines, the cumulative costs (undiscounted) in different HFC phase-down scenarios are estimated at nearly 33–34 billion Euro (2015 prices) in the NA, EU, and SIDS proposals, that is approximately 0.02 percent of India's expected cumulative GDP in the period 2015 to 2050. At the same time, there are significant cost savings (53 billion Euro) primarily in the residential air-conditioning sector due to the lower cost of the alternative refrigerant (HC-290) as well as higher energy efficiency.

2 This number is slightly higher compared to Chaturvedi et al. (2015) as this study also includes HFC emissions from industrial refrigeration and HCFC-22 production for feedstock applications.

Table 1: Cumulative mitigation potential and costs in different HFC phase-down scenarios between 2015 and 2050

HFC phase-down proposals	Cumulative mitigation potential (Gt CO_2eq)	Foregone cumulative mitigation (Gt CO_2eq)	Cumulative cost (Billion Euro)	Cumulative savings (Billion Euro)	Annual emissions in 2050 (Mt CO_2eq)
NA proposal	6.14	0.25	33.24	-53.23	2.0
EU proposal	6.14	0.24	33.50	-53.28	2.4
SIDS proposal	6.16	0.22	34.03	-53.28	1.4
Indian proposal	4.23	2.16	11.59	-48.88	18.9
Intermediate proposal	6.11	0.28	32.60	-53.66	2.4

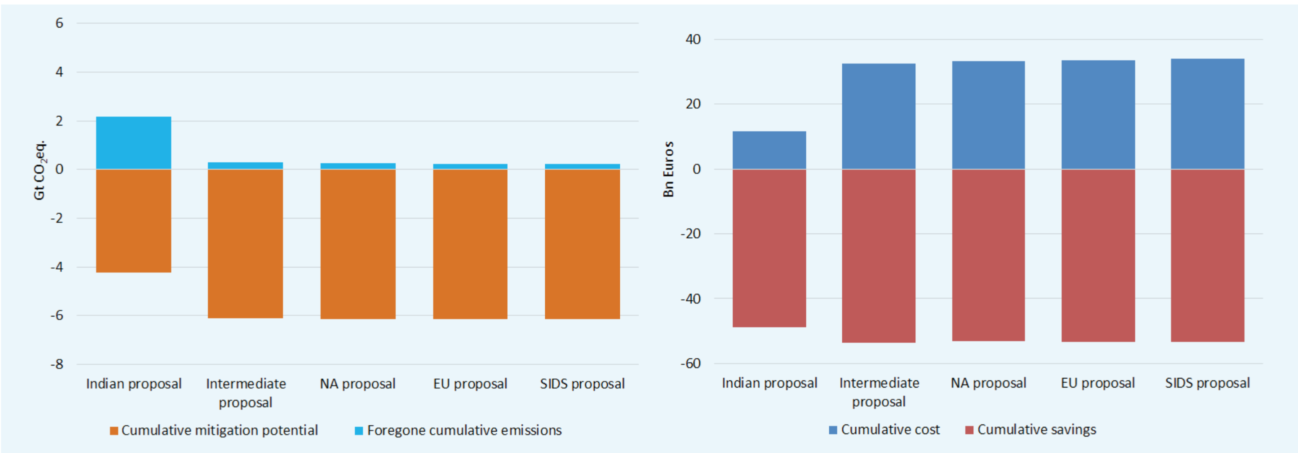
Note: - Costs are cumulative undiscounted costs and in terms of 2015 prices

-The maximum technically feasible mitigation potential is estimated at 6.4 Gt CO_2eq for the period 2015–2050.

It is useful to note that both the mitigation potential and the cost for the EU and NA proposals are similar. This can be explained by comparing the base year and the final phase-down target year for Article 5 parties in both the proposals. The NA proposal has an earlier baseline of average 2011–13 values as compared to the baseline of 2015–16 for the EU proposal, and both proposals target 15 percent of the respective values in the final target phase-down year. But the target year for the final phase-down is later in the NA proposal (2046) compared to that in the EU proposal (2040). The respective freeze years are 2021 and 2019 for the NA and EU proposals. Thus, the NA proposal has a lower baseline, but gives a longer time period for phasing down HFC emissions as compared to the EU proposal. Given that there is little change in Indian HFC emissions between 2011 and 2016, the overall mitigation potential and cost come out to be similar in both the proposals.

The cumulative mitigation cost of the Indian proposal is nearly one-third (11.6 billion Euro) as compared to that of other proposals due to the later start of the controls for Article 5 parties as compared to other proposals. The lower cost also reflects the lower mitigation to be undertaken under the Indian proposal. The fact that the Indian proposal is able to achieve two-thirds of the mitigation as compared to the other proposals at one-third of the cost shows that different sectors face different costs of transition and that there is an upward-sloping marginal abatement cost curve across sectors. HFC emission mitigation as per the Indian proposal relates to the initial part of the marginal abatement cost curve, and as mitigation is pushed further and further beyond this point, the marginal cost rises rapidly. At the same time, there are significant cost savings (49 billion Euro) in the Indian proposal as well, primarily in the residential air-conditioning sector, due to the reasons mentioned earlier.

Figure 3: Cumulative mitigation potential, foregone cumulative emissions, and cumulative costs[3] and saving under different HFC phase-down scenarios in the period 2015 to 2050



3 Economy-wide costs, as calculated in the study, offer a different view on costs estimated by the Multilateral Fund of the Montreal Protocol, which addresses the issue of the loss of profits as well as the incremental cost of conversion at the company level.

There are significant opportunities to reduce HFC consumption and emissions in India if the technical and financial challenges (e.g. flammability and safety, patents, performance in high ambient conditions) to the adoption of alternatives available for various sectors are overcome. The results indicate that more than a third of the mitigation potential is attainable at zero or below zero marginal cost primarily due to inexpensive low-GWP alternatives and energy-efficiency benefits. Tracking energy-efficiency opportunities is in India's self-interest, and appropriate domestic policies can help achieve and accelerate the transition to low-GWP alternatives. Therefore, adequate domestic policy measures are required to increase incentives and to adopt regulations for more energy-efficient appliances in the phase-out of HCFCs and the phase-down of HFCs. At the sectoral level, applications using HFCs (except HFC-134a which is primarily used in mobile air-conditioners and domestic refrigerators) are currently still at an early stage in India. Further, low-GWP (i.e. HC-290 in residential air conditioning) or zero-GWP (i.e. ammonia in industrial refrigeration) substitutes or technologies are already commercially available for several HFC-consuming sectors. However, as in other Article 5 parties, there are currently no domestic regulations for phasing down HFCs in India, unlike the case of national regulations in Japan and the United States and regional regulations in the EU (i.e. F-gas regulation EC 217/2014, MAC Directive 2006/40/EC, etc.) to limit the use of high-GWP HFCs. Thus, concerted efforts are needed at the policy front to promote low-GWP alternatives by developing and implementing appropriate regulations (leakage control, improved components, end-of-life recollection, sectoral bans on high-GWP refrigerants, etc.). These efforts, of course, have to be supported by an agreement at the international level that seeks to achieve HFC consumption and production phase-down at the global level and that ensures that technical and financial support mechanisms are in place. It may be noted that our results are contingent on the best available information on the availability and cost of low-GWP alternatives currently being discussed. Therefore, if new alternatives emerge for different sectors with different technical (i.e. removal efficiency, GWP, etc.) or cost characteristics as compared to the currently discussed alternatives, our quantified results and key insights may change significantly.

In terms of policy insights and actions, our analysis proposes two key action points as immediate steps. The first is the creation of a dedicated institutional structure for supporting R&D for low-GWP alternatives for different sectors and applications, particularly HC-290 for the room air-conditioning sector. Room air-conditioning is expected to be a high-growth sector, and currently there is only one low-GWP solution for this sector—HC-290. However, some sections of Indian industry are sceptical about the applicability of this refrigerant under all conditions, and have expressed concerns about safety. Our analysis shows that there is a huge opportunity for saving electricity through the adoption of this refrigerant. Strategic R&D is the only way that India can harness this opportunity during the transition. Second, Indian stakeholders need a better understanding of the cost of HFO-1234yf (which is being offered as a technically viable solution for the mobile air-conditioning sector) and also the extent to which this cost can decline even in the long term. The current price of this refrigerant in the Indian market is 20 times that of HFC-134a, the most widely used refrigerant at present. This price will drop significantly in the long run with economies of scale. Still some Indian experts believe that the long-run price could be seven to eight times higher than HFC-134a due to application patents as well as the chemistry of this molecule. Our analysis is based on this assumption. An in-depth analysis is required to understand the ways in which this potential cost could be reduced. If such an analysis finds that the potential long-term cost will not be seven or eight times, but only three times, then the estimated economic burden could be reduced by 15-20 percent (as the cost of the additional heat exchanger is also a part of the additional cost). Decline in heat exchanger related cost will further reduce the economic burden. There would still be an economic burden on the country due to the transition, which could be justified as the cost the country is willing to bear for mitigating global warming due to HFCs. It is important to understand this issue and find ways and strategies to minimise the potential economic burden.

The numbers emerging from our analysis are not set in stone and could change as our understanding of the underlying information changes. The two key points mentioned above highlight the strategies required for maximising the potential economic savings and for minimising the potential costs. A better understanding of both the issues will place India in a more confident position to evaluate the trade-offs of the HFC phase-down and to take appropriate decisions to address the twin objectives of safeguarding national priorities and of assuming the mantle of global environmental leadership.

1. Introduction

The contribution to global warming of ever-increasing emissions of greenhouse gases (GHGs) from various sources threatens to lead to catastrophic climate changes. The need for mitigation policies for addressing global climate change concerns is an important item on the agenda of current international discourse. The proposed policies range from supply-side fuel-switching options, to demand-side management, to technology interventions related to geoengineering strategies. However, a large part of the action happening on the emission-mitigation front is focused on mitigating carbon dioxide (CO_2). Non-CO_2 gases (CH_4, N_2O, HFC, PFCs, and SF_6) accounted for 24 percent of total GHG emissions in 2010 (IPCC, 2014). The importance of Non-CO_2 gases will keep growing as low-cost carbon-mitigation options start getting exhausted (Höglund-Isaksson et al., 2012). One such critically important category of gases is hydrofluorocarbons (HFCs).

HFCs are potent GHGs and are expected to contribute significantly to global warming by 2050 (Velders et al., 2009; Gschrey et al., 2011; UNEP, 2011; Velders et al., 2014). At present, emissions of HFCs are increasing at a rate of 10–15 percent per year (Velders et al., 2012). If the current mix of HFCs remains unchanged, increasing demand could result in HFC emissions of up to 8.8 gigatonnes (Gt) carbon dioxide equivalent (CO_2eq) per year by 2050 (UNEP, 2015a). This could jeopardize the substantial climate benefits achieved through the Montreal Protocol, which has averted GHG emissions equivalent to more than 135 Gt of carbon dioxide (UNEP, 2012). The key underlying activity drivers for increased usage of HFCs is their use as refrigerants in refrigeration and air-conditioners and in industrial processes as solvents and foaming agents, coupled with the phase-out of ODS under the Montreal Protocol. Although safe for the ozone layer, the continued emissions of HFCs—primarily as alternatives to ODS and also from the by-product emissions of HFC-23 from the continued production of hydrochlorofluorocarbon (HCFC)—will have an immediate and significant effect on the Earth's climate system. It is projected that HFC emissions, without further controls, could partially negate the climate benefits achieved under the Montreal Protocol (USEPA, 2014). Table 1 presents the use of HFC at the sectoral level as an alternative to ODS.

Table 1. Alternatives options (HFCs) at sectoral level for ODS

Sector	CFCs/HCFCs	HFCs
Aerosol	CFC-11/CFC-12	HFC-134a, HFC-152a
Commercial refrigeration	HCFC-22	HFC-404A, HFC-134a, HFC-410A
Domestic refrigerator	CFC-12	HFC-134a
Fire-extinguisher	Halon 1211/Halon 1301	HFC-236fa, HFC-227ea, HFC-23
Foam	HCFC-141b, HCFC-142b	HFC-245fa, HFC-134a, HFC-152a, HFC-365mfc
Ground source heat pump	HCFC-22	HFC-410A
Industrial refrigeration	HCFC-22	HFC-134a, HFC-404A, HFC-23
Solvents	CFC-113	HFC-43-10mee, HFC-365mfc, HFC-245fa, HFC-c447ef
Mobile air-conditioning	CFC-12	HFC-134a
Stationary air-conditioning*	HCFC-22	HFC-404A, HFC-410A, HFC-134a
Transport refrigeration	HCFC-22	HFC-134a, HFC-404A, HFC-507, HFC-410A

**Air-conditioning in residential and commercial sectors*

India is the world's fourth largest carbon dioxide emitter, behind China, the United States, and the European Union. The proposed high-impact policies for GHG emission mitigation are primarily on the supply side and focus either on expanding the share of renewable energy or on increasing the reliance on nuclear energy as per Intended Nationally Determined Contributions (INDCs) submitted by the Indian government to the United Nations Framework Convention on Climate Change (UNFCCC) in Bonn in October 2015 (GoI, 2015). All the energy supply-side strategies are by their nature focused on carbon dioxide, rather than HFCs, which are emitted mainly in the end-use sectors (i.e. residential, commercial, transport, and industry). With more and more people buying room air conditioners (ACs) and air-conditioned vehicles, the rate of HFC emissions will further increase in the absence of any focused abatement policies. Approximately 1.9 million residential AC units were sold in 2010 with an average capacity of 5.07 kW, and the stock for the same year amounts to 9.2 million units (Phadke et al., 2010). The Indian Refrigeration and Air-conditioning Manufacturers' Association (RAMA) reports a 20 percent annual growth rate for the past decade, with 30 percent growth likely for the next five years. Given the continued strong increase in demand, the release of HFCs is expected to increase manifold until 2050 (Akpinar-Ferrand and Singh, 2010).

The majority of refrigeration and air-conditioning systems produced and marketed in India today use HCFC-22, which is an ODS scheduled for phase-out under the MP. The current HCFC schedule for Article 5 parties requires a freeze in consumption by January 2013 at the 2009–10 average and the cutting of national consumption (domestic HCFC production, plus imports and minus exports) by 10 percent by 2015, 35 percent by 2020, 67.5 percent by 2025, and 97.5 percent by 2030, with consumption after 2030 restricted to the servicing of refrigeration and air-conditioning equipment (UNEP, 2007). By 2040, HCFC production and consumption of refrigerants will completely cease. Most Indian companies have reported that they are planning to change from the HCFC-22 refrigerant to HFC-410A or R-410A (a blend of HFC-125 and HFC-32), which has a global warming potential (GWP) of 2088 (IPCC, 2007). Substitution of HCFC-22 by HFCs (e.g., R-410A or HFC-134a) with high GWP will significantly increase the overall contribution of HFCs to India's national GHG emissions.

Low-GWP (with zero ODP) or cleaner alternatives for HFCs are already available in the market, although with limited penetration due to a variety of reasons (Höglund-Isaksson et al., 2013). Quick action to address the issue of high-GWP HFCs would also catalyse gains in energy efficiency in refrigeration and air-conditioning systems (Carvalho et al., 2014; Borgford-Parnell et al., 2015), thereby reducing electricity use and associated CO_2 emissions (Chaturvedi and Sharma, 2015), consistent with past transitions under the Montreal Protocol, along with emissions of the HFCs themselves. Therefore, policies and cost-effective strategies for mitigation of HFCs are important issues for deliberation for India. At present, India is in the early stages of phasing out HCFCs as per the revised Montreal Protocol (MoEF, 2013). Due to the significantly high GWP of conventional alternatives like HFCs, it is critically important to understand the growth in HFC emissions if no actions are taken to replace these in different activities, and to find the potential and associated costs for HFC reduction in different sectors. This is the broader research objective of our study. In this study, we model alternative scenarios to understand the implications of alternative future global and domestic actions on the HFC front for Indian emissions and industry.

The report is set out as follows: Section 2 presents the GAINS methodology for emission estimation and costs. HFC emissions by sector in the reference and maximum technically feasible reduction (MTFR) scenarios are presented in Section 3. Section 4 presents the mitigation cost curves for the MTFR of HFC emissions in India. Alternative policy scenarios based on the several Montreal Protocol amendment proposals for HFC phase-down are analysed in Section 5. Section 6 highlights uncertainties associated with key assumptions and inputs parameters (leakage rates, costs, etc.), and discusses the sensitivity of the baseline, freeze-in, and phase-down schedules of the HFC phase-down proposals. Conclusions and policy implications are discussed in Section 7.

2. Methodology

2.1 HFC emissions in GAINS

2.1.1 General emission estimation methodology

The methodology adopted for the estimation of current and future GHG emissions and the available potential for emission controls follows the standard GAINS methodology (Amann et al., 2008; Purohit et al., 2010; Amann et al., 2011) with some modifications specific to the F-gases (HFC, PFCs, and SF_6). To accommodate the wide spread in GHG warming potentials for different HFCs, the emission factors are converted to CO_2 equivalents by multiplying with the respective GWPs. Emissions of each pollutant *p* are calculated as the product of the activity levels, the "uncontrolled" emission factor in the absence of any emission control measures, the efficiency of emission control measures, and the application rate of such measures:

$$E_{i,p} = \sum_{j,k,f} E_{i,j,f,t} = \sum_{j,k,f} A_{i,j,k} ef_{i,j,t}\, GWP_p \left(1 - eff_t\right) X_{i,j,f,t} \qquad (1)$$

where *i, j, t,* and *f* respectively represent the country, sector, abatement technology, and fuel; $E_{i,p}$ represents the emissions of the specific pollutant *p* in country *i*; *A* represents the activity in a given sector; *ef* represents the uncontrolled emission factor; GWP_p is the global warming potential of pollutant *p*; $eff_{k,p}$ is the reduction efficiency of abatement option *k*; and *X* is the actual implementation rate of the considered abatement.

If no emission controls are applied, the abatement efficiency equals zero ($eff_{k,p} = 0$) and the application rate is one ($X = 1$). In that case, the emission calculation is reduced to the simple multiplication of the activity rate by the "uncontrolled" emission factor. For projecting emissions into the future, the "uncontrolled" emission factor is assumed to be constant over time, but activity levels may change as a result of exogenous autonomous developments. For example, more cars using mobile air conditioning or an increase in residential air-conditioners will result in higher activity levels of the specific source category. Declines in emissions due to targeted emission control measures are reflected in the GAINS model through the actual implementation rate "*X*" of the considered option. Cases where there is clear evidence that average emission factors change over time due to autonomous (policy-independent) developments (e.g., increased volumes of refrigerant used per refrigerator) are represented in the GAINS model as transitions to different source categories with different uncontrolled emission factors.

2.1.2 Activity data

The estimation of HFC emissions in the GAINS model differs from the estimation of other air pollutants in that the activity data is related to the demand for HFCs, which in an intermediate step has been derived from primary activity drivers like population, GDP, number of vehicles, and value added in industry or the commercial sector. The GAINS model relies on externally provided projections of primary drivers. For the particular analysis presented in this report, the primary drivers for India until 2050 are taken from the integrated assessment modelling framework of GCAM,[4] the Indian Institute of Management Ahmedabad (IIMA) version (Shukla and Chaturvedi, 2012; Shukla and Chaturvedi, 2013; Chaturvedi et al., 2014; Chaturvedi and Sharma, 2015). Further details on modelling are available in Chaturvedi et al. (2015).

A particular characteristic of a large fraction of HFC emissions is that they result both from the release of HFC during the lifetime of appliances (e.g., leakage from refrigerators and air-conditioners) as well as from their scrapping at the end of life. The former emissions are referred to as “emissions banked in equipment” and the latter are referred to as “emissions from scrapped equipment”, i.e. end-of-life emissions. These two types of emission sources are represented as different activity sources in the GAINS model. However, in the representation of the marginal mitigation cost curve, the two sources are joined because the identified mitigation options address both sources simultaneously.

2.1.3 Emission factors

HFC emissions from different sectors are calculated using an emission factors approach where general assumptions are used for determining leakage rates at different stages of HFC use and at the disposal stage at the end of life of appliance and equipment. To the extent available, source-specific emission factors are taken from published literature (IPCC/TEAP, 2005; Gschrey et al., 2011; Schwarz et al., 2011; IPCC, 2007) and complemented by information from industry experts (Chaturvedi et al., 2015). Emission factors are sector specific, with GWPs being determined on the basis of the sector-specific shares of the different types of commonly used HFCs and their respective GWPs. Table 2 presents sector-specific GWPs used in GAINS for India, expressed in CO_2 equivalents over 100 years as presented in the IPCC’s Fourth Assessment Report (AR4) (IPCC, 2007). For a more comprehensive description of calculation methods, references, and sources of uncertainty, see Chaturvedi et al. (2015).

Table 2. Sector-specific global warming potentials (GWPs) used in GAINS

Sector	Type of refrigerant	GWP (100 year)
Aerosol*	HFC-134a	1,430
Commercial air-conditioning*	HFC-410A (50% HFC-32, 50% HFC-125)	1,870
Commercial refrigeration	HFC-134a/HFC-404A (44% HFC-125, 4% HFC-134a, 52% HFC-143a)	2,226
Domestic refrigeration	HFC-134a	1,430
Industrial refrigeration	HFC-134a (62%)/ HFC-404A (37%)/ HFC-23 (1%)	2,486
Mobile air conditioning**	HFC-134a	1,430
Refrigerated transport	HFC-410A (50% HFC-32, 50% HFC-125)	2,088
Transport refrigeration	HFC-134a (80%)/ HFC-404A/ HFC-507 (18%)/ HFC-410A (2%)	1,902
Foam+	HFC-134a (50%), HFC-152a (50%)	777
Solvents	HFC-43–10mee (51.2%), HFC-365mfc (48.8%)	1,227
Other HFC	HFC-134a	1,,430
HCFC-22 production++	HFC-23	22,800

*Stationary air-conditioning includes both commercial and residential air-conditioning; **Mobile air-conditioning includes buses, cars, light- and heavy-duty trucks. and rail air-conditioning; +Foam includes both one-component foams and other foams; ++HCFC-22 production for both emissive and feedstock use.*

Source: (IPCC/TEAP, 2005; IPCC, 2007; Gschrey et al., 2011; Schwarz et al., 2011; Chaturvedi et al., 2015).

4 The Global Change Assessment Model (GCAM), developed by the Pacific Northwest National Laboratory (PNNL), is a global integrated assessment model with particular emphasis on the representation of human earth systems, including interactions between the global economic, energy, agricultural, land use, and technology systems.

2.2 HFC control and cost estimation in GAINS

2.2.1 Technically feasible HFC control options

In the reference scenario, it is assumed that the current level of control reflects the incentives offered by existing legislation to control HFC emissions and that no further control will be adopted in the future unless further policy incentives are implemented. The reference scenario is therefore also referred to as the Current Legislation Emissions (CLE) scenario, and it is assumed for India that the current level of control will remain fixed in the future irrespective of the costs of implementing further emission reductions. Any additional mitigation potential is referred to as the Maximum Technically Feasible Reduction (MFR) scenario.

The mitigation potential assessed here encompasses reductions in emissions through the application of technologies that are currently commercially available and implemented, at least to a limited extent. Appendix II summarizes mitigation options for HFC emissions in the GAINS model. These fall into four broad categories:

a) *Good practice*: This encompasses a package of measures including improved components, leak prevention during use and refill, maintenance, and end-of-life recovery and recollection of refrigerants.

b) *Switching to low-GWP HFCs*: HFCs currently in use have relatively long atmospheric lifetimes—15 years on average—which makes GWPs relatively high, ranging from 1,430 to 14,800 times that of CO_2 over 100 years (IPCC, 2007). Alternative HFCs offer shorter lifetimes and considerably lower GWPs, e.g., HFC-152a has a GWP of 124 (IPCC, 2007).

c) *Switching to new refrigerants*: In recent years, alternative substances with very short lifetimes of less than a few months have been developed and marketed, e.g., HFO-1234ze with a GWP of 6 for use in aerosols and foam products and HFO-1234yf with a GWP of 4 for mobile ACs.

d) *Other non-HFC substances with low or zero GWP*: Commercial examples include hydrocarbons (e.g. propane, isobutane, propylene, and pentane), carbon dioxide (CO_2), ammonia (NH_3), dimethyl ether (DME), and a diversity of other substances used in foam products, refrigeration, air-conditioning, and fire-protection systems.

2.2.2 Mitigation cost per activity unit

Mitigation costs are measured as the additional cost involved in reducing emissions relative to the current level of control as specified in the reference scenario. For example, the cost of substituting the current use of a high-GWP for a low-GWP refrigerant is measured as the difference in price between the two substances and any other costs involved, e.g., necessary equipment modifications. The options for controlling HFC emissions are primarily switches to alternative substances or the adoption of good practices. The relative efficiency in removing GHG emissions of the alternative substances is reflected in the relative GWPs of the substances. As these are assumed to be fixed, we do not assume significant improvements in these removal efficiencies over time. What could be expected in the future is a decline in the cost of some of the alternative substances, e.g., the cost of the newly developed HFO substances for coolants. The current costs of these substances are, however, highly uncertain, and we base our assumption of the long-term cost on the best estimate available from industry experts. Hence, technological development in the mitigation of HFCs under the GAINS model is only reflected in terms of switches to more effective technologies over time, while costs and removal efficiencies for given technologies remain constant.

HFC mitigation costs per unit of activity in the GAINS model are calculated as the sum of investment costs, non-energy operation and maintenance (O&M) costs, and energy-related costs (or savings). In this particular analysis, a social interest rate of 4 percent is assumed. The unit cost of technology m in country i and year t is defined as:

$$C_{itm} = I_{im}\left[\frac{(1+r)^T \times r}{(1+r)^T - 1}\right] + M_{im} + \left(E_{im} \times p_i^{electr}\right) \tag{2}$$

Where $I_{im}\left[\frac{(1+r)^T \times r}{(1+r)^T - 1}\right]$ is the annualized investment cost for technology *m* in country *i* and with an interest rate *r* and a technology lifetime of *T* years, M_{im} is the non-energy-related annual O&M cost for technology *m*, E_{im} is the change in demand for electricity, and p_{it}^{electr} is the electricity price in country *i* in year *t*. The price of electricity in India is assumed to increase from 0.07 to 0.1 Euro/kWh between 2010 and 2050 (CEA, 2015).

The intellectual approach adopted for understanding mitigation costs for the HFC phase-down is grounded in the methodology used in climate-policy research. As per this approach, emission mitigation potential is estimated in reference to a 'business-as-usual' scenario, and economy-wide mitigation costs are calculated corresponding to the economy-wide mitigation potential under each alternative policy scenario. The cost-calculation methodology is different from the way costs are calculated under the MLF of the Montreal Protocol. The objective of MLF is to support industries in developing countries (Article 5 parties) in transitioning away from high-GWP HFCs. Given this objective, MLF estimates the loss of profit (or the incremental cost) for industries/companies that will be impacted by a phase-down. The approach taken by this study, on the other hand, estimates the economy-wide costs of a transition, irrespective of who within the economy will bear this cost.

3. HFC emissions by sector and projections

In compliance with the Montreal Protocol, many sectors that formerly used the highly ODS chlorofluorocarbons (CFCs) changed rapidly to applications employing HCFCs with lower ozone-depleting effects or HFCs with no ozone-depleting effects. Later amendments to the Montreal Protocol require a complete phase-out of all ODS, including HCFCs. In the GAINS model, 13 different sources of HFC or HCFC emissions have been identified, whereof seven are related to refrigeration and air conditioning. Table 3 presents the sub-sectors distinguished in the GAINS model for HFC or HCFC emissions. Emissions from refrigeration and air-conditioning sources are split on the basis of emissions from leakage from equipment in use and emissions from scrapping of the equipment at the end-of-life. In addition, for each emission source, the fraction of HCFC to HFC in use is identified and modelled following the phase-out schedule of HCFCs in the latest revision of the Montreal Protocol (UNEP, 2007) and the HCFC Phase-out Management Plan (HPMP) of the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India (MoEF, 2013). It may be noted that under the Montreal Protocol programme in India, the fire-extinguisher sector phased out the use of CFCs. The conversion technologies used were FM200, ABC powder, CO_2, etc. Thus, there is no residual use of HCFCs and HFCs in the fire-extinguisher sector (MoEF, 2009). Information on the number of ground source heat pumps installed in the country is not available, and therefore GSHP is not included in this analysis.

Table 3. Sub-sectors distinguished in GAINS for HFC emissions

GAINS sectors	Description
AERO	Aerosols
CAC_B	Commercial air conditioning using water chilling, emissions banked in equipment
CAC_S	Commercial air conditioning using water chilling, emissions from scrapped equipment
COMM_B	Commercial refrigeration, emissions banked in equipment
COMM_S	Commercial refrigeration, emissions from scrapped equipment
DOM_S	Domestic small hermetic refrigerators, emissions from scrapped equipment
FEXT_B*	Fire extinguishers, emissions banked in equipment
FEXT_S*	Fire extinguishers, emissions from scrapped equipment
GSHP_B**	Ground source heat pumps, emissions banked in equipment
GSHP_S**	Ground source heat pumps, emissions from scrapped equipment
HCFC22_E	HCFC-22 production for emissive use
HCFC22_F	HCFC-22 production for feedstock use
IND_B	Industrial refrigeration, including food and agricultural, emissions banked in equipment
IND_S	Industrial refrigeration, including food and agricultural, emissions from scrapped equipment
SOLV_PEM	Solvents
TRA_RD_HDB_B	Mobile air conditioning in buses, emissions banked in equipment
TRA_RD_HDB_S	Mobile air conditioning in buses, emissions from scrapped equipment
TRA_RD_HDT_B	Mobile air conditioning in heavy-duty trucks, emissions banked in equipment
TRA_RD_HDT_S	Mobile air conditioning in heavy-duty trucks, emissions from scrapped equipment

GAINS sectors	Description
TRA_RD_LD4C_B	Mobile air conditioning in cars, emissions banked in equipment
TRA_RD_LD4C_S	Mobile air conditioning in cars, emissions from scrapped equipment
TRA_RD_LD4T_B	Mobile air conditioning in light-duty trucks, emissions banked in equipment
TRA_RD_LD4T_S	Mobile air conditioning in light-duty trucks, emissions from scrapped equipment
OC	Polyurethane one-component foam
OF	Other foam
RAC_B	Residential air conditioning using water chilling, emissions banked in equipment
RAC_S	Residential air conditioning using water chilling, emissions from scrapped equipment
RAILAC_B	Rail air conditioning using water chilling, emissions banked in equipment
RAILAC_S	Rail air conditioning using water chilling, emissions from scrapped equipment
TRA_REFB	Refrigerated transport, emissions banked in equipment
TRA_REFS	Refrigerated transport, emissions from scrapped equipment

**Not relevant for India.*
***Not included in this analysis.*

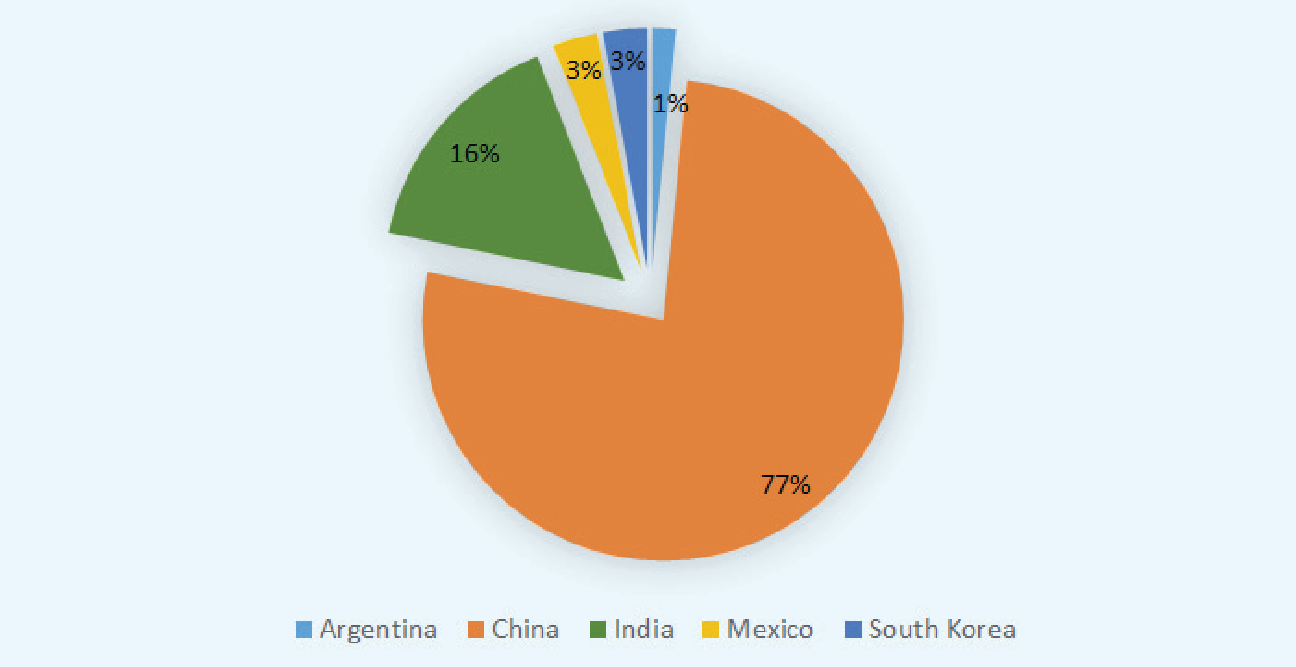
For a more comprehensive description of HCFC/HFC consumption at the sectoral level, leakage rates, and data sources, see Chaturvedi et al. (2015).

3.1 HFC emissions control under CDM regime

The GAINS model distinguishes between several abatement options to reduce HFC emissions from anthropogenic sources. The removal efficiencies, costs, and application potentials of these abatement options were determined based on the data available in the literature (Tohka, 2005; Schwarz et al., 2011; Höglund-Isaksson et al., 2013). HFC emissions in the current legislation or reference scenario take the effects of already implemented control measures into account. So far, India does not have any specific control policies for HFC emissions. However, several studies discuss the impact of the Clean Development Mechanism (CDM) projects on global HFC-23 emissions through HCFC-22 production (Miller et al., 2010; Montzka et al., 2010; Miller and Kuijpers, 2011; Schneider, 2011).

The CDM of the Kyoto Protocol allowed developed countries (referred to as Annex-I countries) to use credits from GHG abatement projects in developing countries (referred to as non-Annex-I countries). The destruction of HFC-23 from HCFC-22 production accounts for 19 of the 23 HFC projects. This has become the most important project type under the CDM, with an expected deliverance volume of 473 million certified emission reductions (CERs) in the period up to 2012 and approximately 1.1 billion CERs by 2020 (Fenhann, 2015). These CER volumes correspond to about a fifth of the emission reductions expected from all CDM projects in this period. Eleven out of the 19 registered projects are located in China, five in India, and one each in South Korea, Argentina, and Mexico. Figure 1 presents the country-based distribution of the average annual CERs from HFC-23 projects registered by the CDM Executive Board in the first commitment period. As shown, India is expected to receive 16 percent of the CERs from these projects.

Figure 1: Expected annual CERs from registered HFC-23 projects



Source: Fenhann (2015).

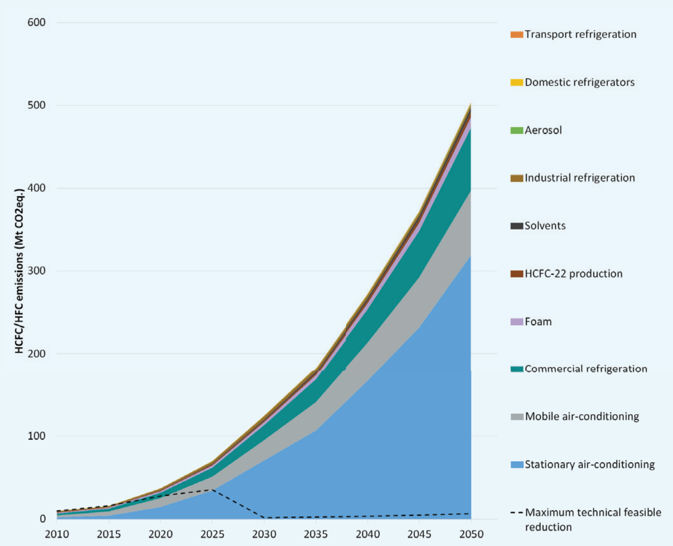
In the reference scenario, we assume that the current impact of CDM on emissions from HCFC-22 production in India will remain at the current level of 100 percent control in the future as well. In the foam sector, three projects on avoidance of HFC-134a emissions in rigid polyurethane foam (PUF) from Uttarakhand,[5] Tamil Nadu,[6] and Maharashtra[7] are registered by the CDM Executive Board until October 2015 (Fenhann, 2015). Also, for foams, the current level of control is assumed to be frozen in the future in the reference scenario.

3.2 Projection of HFC emissions by sector

Figure 2 presents the sectoral development of baseline HCFC/HFC emissions in the period 2010 to 2050. Baseline HFC emissions are estimated to increase from 10 Mt CO_2eq (including HCFC emissions) in 2010 to 503 Mt CO_2eq (HFC emissions only) in 2050. The growth is caused mainly by the increase in HFC emissions from refrigeration and air conditioning applications, as shown in Figure 2. The increase in HFC, in turn, represents the combined effect of the replacement of HCFCs with HFCs in accordance with the revised Montreal Protocol and the expected increase in demand for refrigeration and air conditioning.

5 Avoidance of HFC-134a emissions in rigid polyurethane foam manufacturing by Acme Tele Power Ltd. (ATPL).
6 Avoidance of GHG emissions in rigid polyurethane foam manufacturing by LIL.
7 Avoidance of HFC-134a emissions in rigid polyurethane foam.

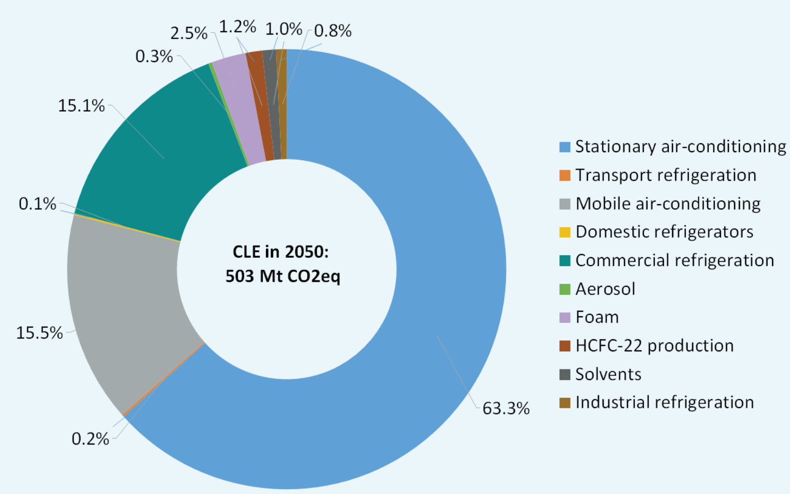
Figure 2: Sectoral development of baseline HCFC/HFC emissions, 2010–2050



In India, the stock of domestic refrigerators is predicted to grow from 48.5 million units in 2010 to 83 million units in 2020, and to 353 million units in 2050, as per CEEW estimates, whereas the stock of ACs is predicted to grow at a much faster pace. The stock of stationary ACs will increase from 2.6 million units in 2005 to 38 million units in 2020, and further to 445 million units in 2050 (Chaturvedi et al., 2015). The stock of ACs in the high-income groups is expected to be larger than the stock of refrigerators in the residential sector in India, which is most likely and is supported by what is already an observed trend in terms of household behaviour. A given high-income household is likely to own only one fridge, but can own two or even three ACs for cooling separate rooms. Accordingly, an exponential increase is expected in stationary air-conditioning for the residential and commercial sector in the period 2010 to 2050.

Figure 3 presents HFC emissions in 2050 by sector for the reference (or CLE) scenario. In 2050, stationary (residential and commercial) air-conditioning is expected to contribute over 63 percent HFC emissions, followed by mobile air-conditioning (15.5 percent) in buses, cars, light- and heavy-duty trucks, and air-conditioned coaches in railways. In 2050, the share of commercial refrigeration is expected to be 15.1 percent of total HFC emissions, followed by foam (2.5 percent) and other sectors (3.6 percent), including industrial/transport refrigeration, aerosols, solvents, etc.

Figure 3: HFC emissions in 2050 by sector for GAINS model domain in the reference scenario



3.3 Maximum technically feasible reduction (MTFR) by sector

There are extensive opportunities for ensuring reductions in HCFC/HFC emissions through existing alternative technologies or through replacement of substances with low-GWP alternatives. Information on potential options to reduce HFCs is presented in Table 4, which indicates alternatives that are currently used on a commercial scale and are considered in the GAINS model for assessing the mitigation potential. The maximum technical mitigation potential is depicted by the dashed line in Figure 2. In 2050, the technical mitigation potential is predicted to be over 98 percent of reference (or CLE) emissions.

Table 4. Low-GWP options at sectoral level

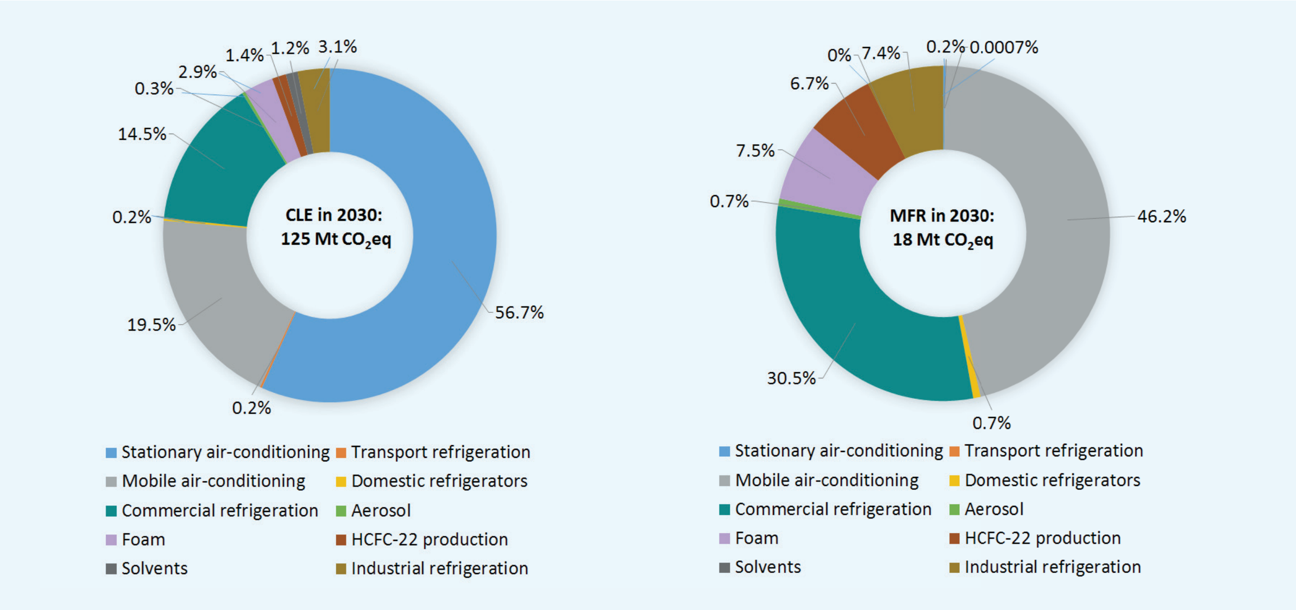
Sector	Alternative low-GWP refrigerants
Aerosol	HFO-1234ze, HFC-152a, Propane (HC-290)
Commercial refrigeration	Propane, Isobutane (R-600a), R-1270, CO_2 (R-744)
Domestic refrigerators	Propane, Isobutane, HFC-1234yf
Fire-extinguisher	FK-5-1-12, FM200, CO_2, ABC powder
Foam	CO_2, Propane, HFC-152a, HFC-1234ze
Ground source heat pumps	CO_2, Propane
Industrial refrigeration	NH_3 (R-717), CO_2
Solvents*	Iso-paraffin/siloxane (KC-6)
Mobile air-conditioning	HFO-1234yf, CO_2, HFC-152a
Commercial air-conditioning	Propane, Propylene (R-1270), CO_2
Residential air-conditioning	Propane, Propylene, CO_2
Transport refrigeration	Propane, Propylene, CO_2

GAINS considers a "ban" on HFC-based solvents as a control option.

India and other countries have raised concerns about the existence of HFC alternatives. These concerns include managing flammability risks associated with some alternatives, finding alternatives that work adequately at high ambient temperatures, and finding alternatives that can be used safely in densely packed urban environments such as India's megacities, New Delhi and Mumbai. While no single technology solution is available, technical experts involved in the Montreal Protocol discussions assert that a basket of alternatives exists for different applications. Some of these options are available today and others are on the horizon for becoming commercially available in the near future (UNEP/TEAP, 2014).

The maximum technical mitigation potential is presented against the reference (CLE) scenario for India, and is depicted by the dashed line in Figure 2. Figure 4 indicates the distribution of emissions across the regions and the changes between the CLE and MFR scenarios. Note that the total amount of HFCs emissions in the MFR case is very much lower than in the CLE case.

Figure 4: Share of different sectors in total emissions in CLE (left panel) and MFR (right panel) scenarios in 2030



In the near term, abatement opportunities in refrigeration and air-conditioning are partially limited because many of the abatement options identified apply only to newly manufactured equipment and are thus limited by the turnover rate of the stock of coolant currently stored in existing refrigeration and air-conditioning equipment. Table 5 presents HFC emissions and technical mitigation potentials in 2050. The maximum technical mitigation potential is depicted by the dashed line in Figure 2. In 2050, the technical mitigation potential will exceed 98 percent of reference (CLE) emissions, hence reducing the expected emissions by over 497 Mt CO_2-eq. in 2050. Major uncertainties affecting the above results are present in the emission factors and activity pathways, as well as in the estimates about the future penetration of mitigation technology, e.g., the use of low-GWP substances in mobile and stationary ACs and refrigerators is uncertain. There is also a general lack of data on reported emissions to verify model emission estimates.

Table 5. Summary results: HFC emissions and technical mitigation potentials in India

Sector	Reference scenario emissions (Mt $CO_{2eq.}$)				Remaining emissions after MTFR in 2050 (Mt CO_2eq.)
	2020	2030	2040	2050	
Aerosols	0.1	0.4	0.8	1.4	0.00
Commercial air-conditioning	5.2	31.2	76.3	140.6	0.08
Commercial refrigeration	6.6	18.2	40.5	76.1	0.03
Domestic refrigeration	0.2	0.3	0.5	0.7	0.00
Foam	1.8	3.6	6.9	12.7	0.05
HCFC-22 production	0.8	1.7	3.3	6.1	6.09
Industrial refrigeration	1.5	3.9	3.9	3.9	0.00
Mobile air conditioning	10.4	24.2	45.5	77.7	0.22
Refrigerated transport	0.1	0.2	0.5	0.8	0.00
Rail air-conditioning	0.1	0.2	0.2	0.3	0.00
Residential air-conditioning	6.9	39.0	90.8	178.4	0.09
Solvents	0.5	1.4	2.8	5.2	0.00
Total	34.2	124.3	272.0	503.8	6.56

Note: HCFC-22 production is for meeting feedstock requirements.

4. Cost curves

The relation between emission control costs and the associated emission control potentials can be displayed in the form of cost functions. Starting from the defined unit costs, the marginal cost is calculated for each mitigation option. When there are several mitigation options available for one sector, the option with the lowest unit cost per tonne CO_2eq removed is assumed to be adopted first before moving on to more expensive options. For example, control of HFCs from air-conditioning and refrigeration is assumed to start from the application of good-practice measures like leakage control and end-of-life recycling before moving on to the replacement of coolants with alternative fluids, as this latter step is usually (but not always) more expensive. The GAINS model distinguishes several abatement options to reduce HFC emissions (Appendix II). The respective removal efficiencies, costs, and application potentials of these abatement options were determined based on data found in the available literature (Harnisch and Schwarz, 2003; Tohka, 2005; Schwarz et al., 2011; Höglund-Isaksson et al., 2012; Höglund-Isaksson et al., 2013; Purohit and Höglund-Isaksson, forthcoming). To verify the relevance of the cost information available in the literature to Indian circumstances, efforts have been made under this project to gather country- specific information from India on the costs of alternative options. Appendix III presents the market price of alternative refrigerants in the Indian market.

HC (HC-290)-based ACs have been available in the Indian market for the last few years and offer an opportunity to switch to low-GWP alternatives that are both low cost and more efficient than many of the HFC-based systems currently in use. Indian AC manufacturers Godrej & Boyce report sales of over 100,000 AC units using HC-290 refrigerant in 2013–14 (NRDC et al., 2013). For example, there is no difference in the market price of HFC-based AC (when 100 percent -410A is used in "single room split") and HC-based AC (when 100 percent HC-290 is used in "single room split") as per the cost-related information provided by the industry (Appendix III). Therefore, the incremental investment cost of switching from R-410A-based AC to HC-290-based AC will be zero. Moreover, the market price of HC-290 as compared to R-410A is less than half in Europe (Schwarz et al., 2011) and significantly lower in India as well. Therefore, the refilling cost of a room AC system using HC-290 will be lower assuming that there is no change in the cost of manpower. As compared to R-410A, HFC-32 can improve energy efficiency by 5–10 percent depending on the model (Daikin, 2016). In this study, we have assumed a 6 percent efficiency gain for both HC-290 based system and HC-32 based system, relative to HFC-410A based system. Therefore, the HC-290-based single room split AC is a low-cost alternative to the R-410A-based AC.

In addition, it is observed that the market price of HFC-32 (GWP100 = 650)-based AC is approximately 10 percent lower to those of R-410A- and HC-290-based ACs. Moreover, the lower market price of HFC-32 as compared to R-410A and efficiency-improvement measures make the HFC-32-based system a low-cost option. Although the GWP is high in the case of HFC-32-based AC as compared to the HC-290-based system, consumers may still go in for the HFC-32-based system because of its somewhat lower investment cost and slightly higher efficiency. Therefore, there might be scope here for introducing climate-policy intervention to make HC-based alternatives more attractive to consumers.

Evidence concerning costs for mobile air conditioners from the B-COOL (2011) project funded by the EU Sixth Framework Program suggests that the cost of a CO_2-based AC system is between 1.5 to 2 times the cost of a HFC-134a system. Moreover, CO_2-based systems show slightly higher fuel consumption at a higher thermal load (35 °C) as compared to the HFC-134a system. This is in contrast to the fuel (diesel/

gasoline) savings claimed by some CO_2 promoters (e.g., www.r744.com). As a compromise, we do not assume any effect on energy consumption when switching to a CO_2-based system in mobile ACs in this analysis.

The primary alternatives to HFC-134a as a propellant in medical dose inhalers are dry powder inhalers (DPI) or HFC-152a, which has a GWP_{100} of about 124. The relative cost of these options is similar to the cost of medical dose inhalers (MDIs) in developed countries (UNEP/TEAP 2010). However, for medical reasons, MDIs are still preferred in severe cases. For severe cases, where high pressure is essential, there is the option of replacing HFC-134a with HFO-1234ze (GWP_{100} of 6), which, according to the manufacturer Honeywell, is already available for use as a propellant for aerosols.

Figure 5 shows the estimated marginal mitigation cost curve for Indian HFC emissions in the period 2020 to 2050 when moving from the reference (CLE) scenario to the MFR scenario. The mitigation potential is extended over time primarily due to the expected increase in the reference scenario emissions. As shown, at a zero or negative marginal cost, 37 percent of the mitigation potential in 2050 is expected to be attainable, while 53 percent is expected to be attainable at a marginal cost between zero and 20 €/t CO_2eq, 7 percent at a marginal cost between 20 and 50 €/t CO_2eq, and the removal of the last 3 percent is expected to come at a high cost exceeding a marginal cost of 50 €/t CO_2eq (Figure 5).

Figure 5: Marginal mitigation cost curve for maximum technical reduction of HFC emissions in India in 2020, 2030, 2040, and 2050.

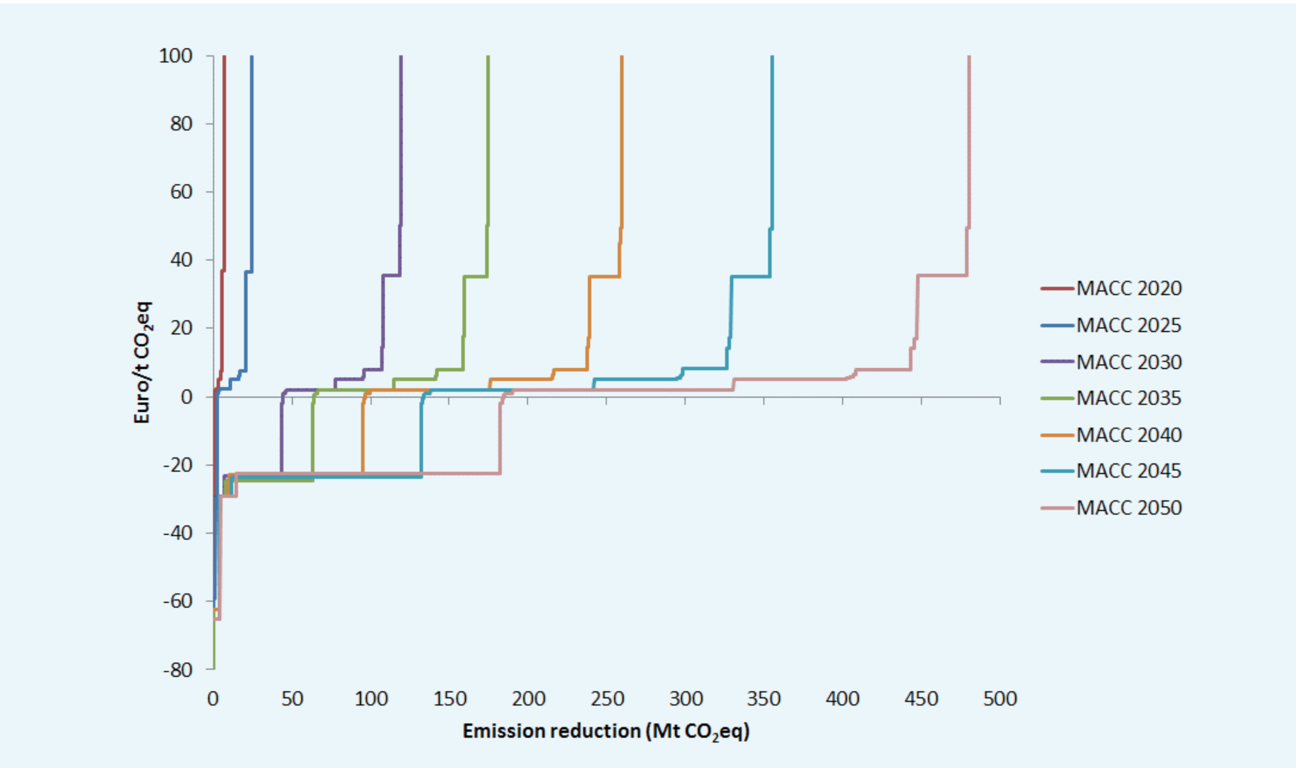
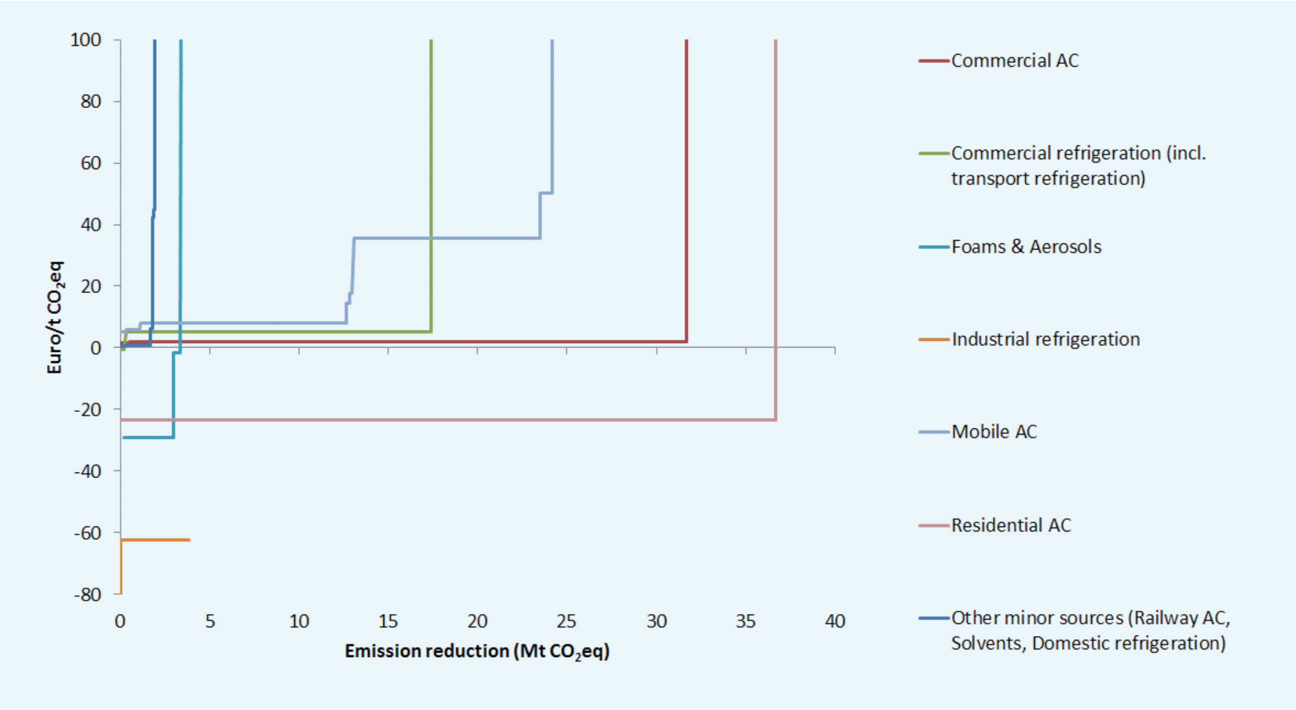


Figure 6 shows the marginal mitigation cost curves by sector in the year 2030. The mitigation potential is high and is inexpensive for the residential air-conditioning, industrial refrigeration, and aerosol/foam sectors due to the availability of less expensive alternatives (HCs, NH_3, HFC-152a, etc.) to HFCs and the high removal efficiency of alternative refrigerants (i.e. in case of room ACs). For commercial air-conditioning, commercial and transport refrigeration, etc., the mitigation potential is high and is relatively inexpensive as compared to mobile air-conditioning. For mobile ACs, good-practice options to control leakage and end-of-life recollection schemes are relatively inexpensive at below 10 €/t CO_2eq. The reduction potential of the good-practice options is exhausted first before moving on to the more expensive options of replacing the use of HFCs with HFO-1234yf and pressurised CO_2.

Figure 6: Marginal mitigation cost curve for maximum technical reduction of HFC emissions in India in 2030 by sector.



5. Alternative policy scenarios for HFC phase-down

At the international level, there is growing recognition that HFCs can be controlled most effectively through the phase-down of their production and consumption under the Montreal Protocol as a complement to controls on emissions under the Kyoto Protocol (Zaelke and Borgford-Parnell, 2015). The projected growth and the expanded use of HFCs under the current status quo may make them the most potent and high-impact GHGs. So, there is concern that if they are not controlled, climate change will increase significantly over time. The United States, Canada, and Mexico together submitted a proposal in April 2015 to phase-down the production and consumption of HFCs under the Montreal Protocol (UNEP, 2015b). In addition to the North American proposal, the European Union (UNEP, 2015c), India (UNEP, 2015d), and a group of Small Island Developing States (SIDS) of the Pacific region (UNEP, 2015e) submitted their own proposals in 2015 to amend the Montreal Protocol to address the issue of HFC emissions. In each proposal, the annual production and consumption of HFCs in Article 5 and non-Article 5 parties are reduced following phase-down schedules relative to specified base levels. The base level and HFC phase-down schedules for Article 5 and non-Article 5 parties as per the 2015 Montreal Protocol amendment proposals (UNEP, 2015b–e) are presented in Appendix IV (UNEP, 2015b–e). All of the proposed amendments to the Montreal Protocol provide a flexible phase-down with financial and technological assistance through the MLF to address the needs of different countries.

The *North American (NA) proposed amendment* was submitted by Canada, Mexico, and the United States. It lists 19 HFC chemicals as substances to be controlled and provides access to the MLF to cover incremental costs. Article 5 parties receive a two-year grace period, and the phase-out schedule is different for Non-Article 5 parties and Article 5 parties, as shown in Appendix IV. It is estimated to avoid 60–75 Gt CO_2eq of global GHG emissions by 2050 (Velders et al., 2015).

The *European Union* proposed amendment was submitted by the 28 member states of the EU. It addresses 19 HFCs, split up into five groups, allows access to the MLF for incremental costs, puts forward a phase-down schedule for Non-Article 5 parties, and outlines a freeze in consumption for Article 5 parties in the short term. In the EU proposal, there are different controls for HFC production and consumption in Article 5 parties, as shown in Appendix IV. Global cumulative benefits of the HFC consumption freeze and a production reduction in Article 5 parties, as well as the phase-down of both production and consumption in non-Article 5 parties, amount to a reduction of 79 Gt CO_2eq by 2050 (UNEP, 2015c).

The *Small Island Developing States (SIDS) amendment* was submitted by Kiribati, the Marshall Islands, Mauritius, the Federated States of Micronesia, Palau, the Philippines, Samoa, and the Solomon Islands. It addresses 22 specific HFCs and HFOs as controlled substances, allows access to the MLF for the fully agreed upon incremental costs, provides for a three-year grace period, and delineates a different phase-out schedule for Non-Article 5 parties and Article 5 parties. It could result in the reduction of 60–73 Gt CO_2eq global GHG emissions for the 2015–2050 period (Velders et al., 2015).

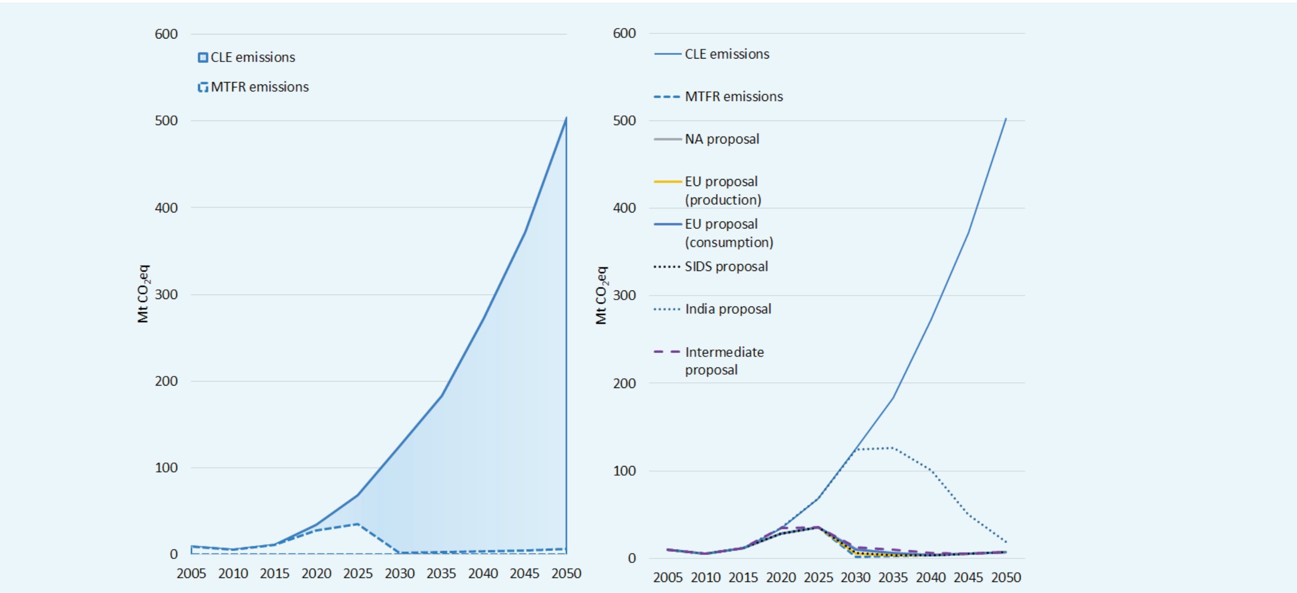
The *Indian proposed amendment* addresses 19 HFC substances divided into four groups. It controls HFCs starting in 2016 for Non-Article 5 parties and starting in 2031 for Article 5 parties, thereby allowing Article 5 parties a 15-year grace period. It proposes MLF support for full conversion costs for Article 5 parties. Where the other proposals call for covering the agreed incremental costs (the approach currently used under the Montreal Protocol), India proposes including the MLF payment for full conversion costs. India's proposal would avoid an estimated 25–36 Gt CO_2eq global GHG emissions by 2050, as per Velders et al. (2015).

The African Group non-paper was submitted by 54 African countries. It addresses 21 HFC substances divided into two groups and provides access to the MLF on an unconditional basis for Article 5 parties. While it does not outline specific schedules or timeframes, it does indicate that controls, freezes, baselines, and grace periods should be determined by the available technology and should be guided by the principle of common but differentiated responsibilities.

The base level is different for Article 5 and non-Article 5 parties among all the amendment proposals, as shown in Appendix IV. For both non-Article 5 and Article 5 parties, the base level is defined by a combination of both HFC and HCFC use, while for non-Article 5 parties this implies that the level is primarily determined by the historical use of HFC (Appendix IV). The phase-down (in CO_2eq) in HFC consumption (and production) in each proposal can be achieved through a wide range of strategies. The strategy assumed in this analysis is to reduce high-GWP HFCs in a cost-effective manner, as discussed in Section 4. Although not considered in this analysis, other possible phase-down strategies include reducing high-GWP HFC use equally in all sectors (Velders et al., 2015) or following the same consumption phase-down, but first targeting certain HFCs, such as HFC-143a (GWP_{100} = 4,470) as per IPCC/AR4, that have longer atmospheric lifetimes than the most commonly used HFCs.

Figure 7 presents India's HFC emissions in the CLE (i.e., current legislation or baseline) scenario in comparison with the MTFR scenario (left panel) and the alternative policy scenarios (right panel) as outlined by the different amendment proposals to the Montreal Protocol. We have used the emission baseline instead of the consumption baseline in this study to assess the mitigation potential and the associated costs in different amendment proposals. For developing countries, the phase-down schedules are not fully specified in the EU and Indian proposals; therefore, some intermediate reduction steps are assumed in the present analysis (Appendix IV). It may be noted that HFC emissions in the GAINS model are modelled in each five-year interval. Therefore, the HFC phase-down has been adjusted accordingly. The HFC reduction steps (actual and adjusted for the GAINS model) for Article 5 parties are presented in Appendix V. As expected, HFC emissions are phased out significantly in the NA, SIDS, and EU proposals by 2030 as compared to the Indian proposal in which the HFC consumption and production freeze is proposed in 2030–31.

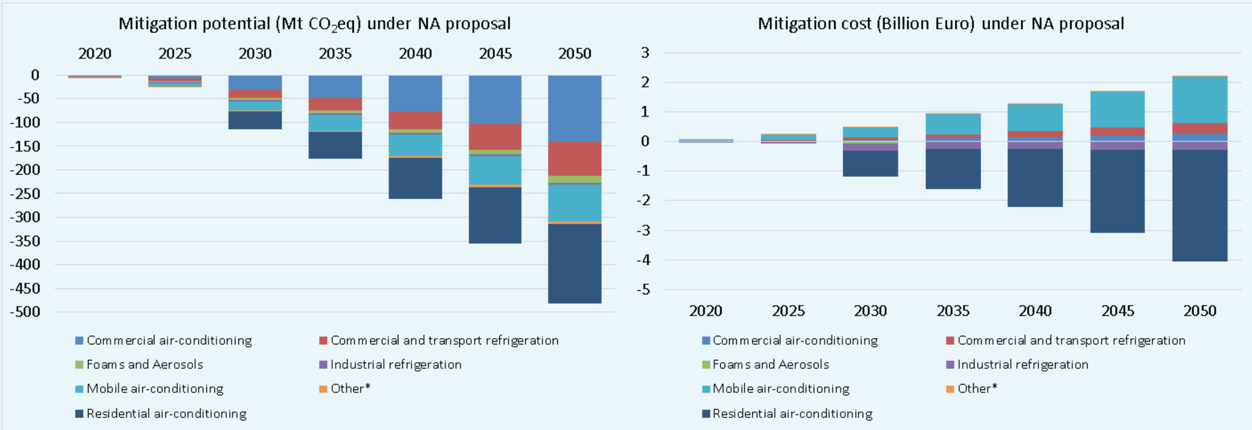
Figure 7: HFC emissions in MTFR (left panel) and HFC phase-down (right panel) scenarios for India



5.1 The North American, European, and SIDS Proposals

Figure 8 presents the mitigation potential and costs for India under the North American (NA) proposal. Mitigation potential is estimated at 114 Mt CO_2eq for 2030 and at 482 Mt CO_2eq for 2050. It may be noted that mitigation above the marginal abatement cost of 200 Euro per tonne CO_2eq is not considered in this analysis. There is a large mitigation potential in stationary air-conditioning, followed by the mobile air-conditioning and commercial refrigeration sector. The cumulative mitigation for the period 2015 to 2050 as per the NA proposal is estimated at 6.14 Gt CO_2eq. There are several negative-cost options available for switching from HFCs to alternative refrigerants. The highest cost-saving potential is estimated for residential ACs and the foam sector due to the price differential in current HFCs and HCs as alternative options.

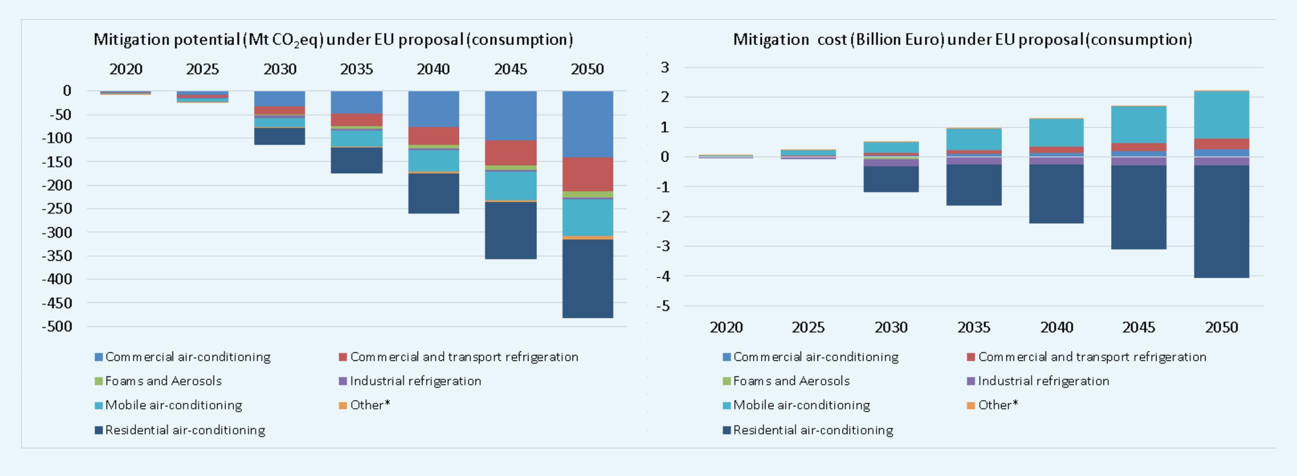
Figure 8: Mitigation potential and costs under the North American proposal



In the EU proposal, there are different controls for HFC production and consumption in developing countries. It is mentioned that the intermediate reduction steps are to be determined by 2020 for both production and consumption in developing countries. In this study, we have assessed the mitigation potential and costs under the EU proposal for consumption (Appendix IV). The EU production proposal targets 15 percent of baseline production in 2040. In view of uncertainty about the reductions steps, we have assumed that by 2040 HFC consumption will be 15 percent of the baseline consumption.

Figure 9 presents the estimated mitigation potential and costs under the European Union (EU) proposal. The mitigation potential is estimated at 115 Mt CO_2eq in 2030 and at 482 Mt CO_2eq in 2050, whereas the cumulative mitigation potential for the period 2015 to 2050 as per the EU proposal is estimated at 6.14 Gt CO_2eq approximately, equivalent to the mitigation potential estimated using the NA proposal at a marginal abetment cost of <200 Euro.

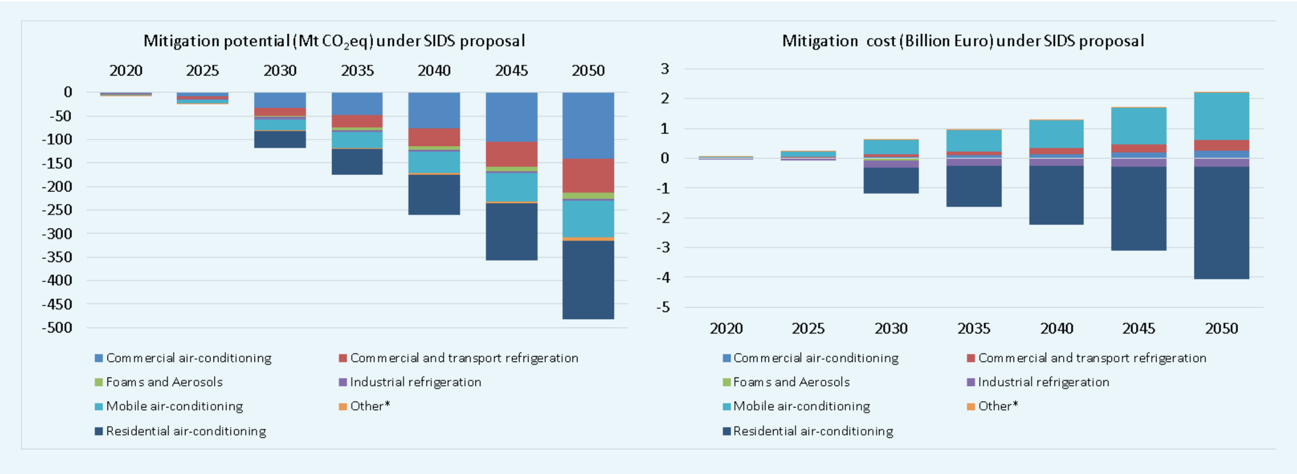
Figure 9: Mitigation potential and costs under the EU proposal



It is useful to note that both the mitigation potential and the cost for the EU and NA proposals are similar. This can be explained by comparing the base year and the final phase-down target year for Article 5 parties in both the proposals. The NA proposal has an earlier baseline of the average 2011–13 values as compared to the baseline of 2015–16 for the EU proposal, and both proposals target 15 percent of the respective values in the final target phase-down year. But the target year for the final phase-down is later in the NA proposal (2046) compared to that in the EU proposal (2040). The freeze years for the NA and EU proposals are 2021 and 2019 respectively. Thus, the NA proposal has a lower baseline, but gives a longer time period for phasing down HFC emissions as compared to the EU proposal. Give that there was little change in Indian HFC emissions between 2011 and 2016, the overall mitigation potential and costs come out to be similar in both the proposals.

Figure 10 presents the estimated mitigation potential and costs under the SIDS proposal. The mitigation potential is estimated at 118 Mt CO_2eq in 2030 and at 482 Mt CO_2eq in 2045, whereas the cumulative mitigation potential for the period 2015 to 2050 as per the SIDS proposal is estimated at 6.16 Gt CO_2eq approximately, equivalent to the mitigation potential estimated using the NA and EU proposals at a marginal abetment cost of <200 Euro.

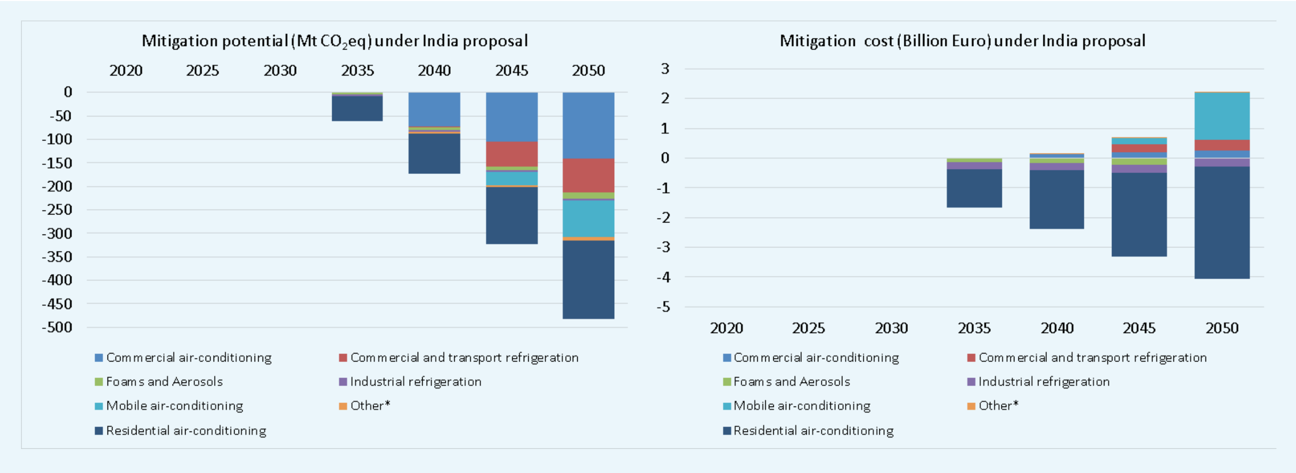
Figure 10: Mitigation potential and costs under the SIDS proposal



5.2 The Indian Proposal

Figure 11 presents the mitigation potential and costs under the Indian proposal. The mitigation potential is estimated at 173 Mt CO_2eq in 2040 and at 482 Mt CO_2eq in 2050, whereas the cumulative mitigation potential for the period 2015 to 2050 as per the Indian proposal is estimated at 4.2 Gt CO_2eq at a marginal abetment cost of <200 Euro.

Figure 11: Mitigation potential and costs under the Indian proposal



The cumulative mitigation cost in the Indian proposal is almost 12 Bn Euros, which is much less compared to the other proposals. This is because mitigating each additional unit of HFCs is more expensive than mitigating the last unit due to the rising marginal abatement cost. However, the cumulative mitigation achieved in the Indian proposal is also lower. This inherently reflects the trade-off faced by policy makers, More mitigation is more costly, and the additional economic burden is imperative for achieving higher environmental benefit.

5.3 An Intermediate Proposal

It is observed that the grace period (beyond the beginning of the non-Article 5 control period) is five years in the NA proposal and seven years in the SIDS proposal, whereas the Indian proposal provides for a 15-year grace period. Therefore, in this study, we have analysed an intermediate policy proposal with a grace period of seven years. In this scenario, we assume that the freeze year for Article 5 countries is 2025, while the base year is the same as in the NA proposal. Keeping the base year the same as in the NA proposal while shifting the freeze year closer to the one in the Indian proposal tests the sensitivity of emission mitigation to both the base year and the freeze year. Figure 12 presents the mitigation potential and costs under the so-called intermediate policy proposal in which the mitigation potential is estimated at 116 Mt CO_2eq in 2030 and at 482 Mt CO_2eq in 2050, whereas the cumulative mitigation potential for the period 2015 to 2050 as per an intermediate policy proposal is estimated at 6.1 Gt CO_2eq approximately, equivalent to the mitigation potential estimated using the NA, EU, and SIDS proposals at a marginal abatement cost of <200 Euro. This result shows that for the analysed time frames, an earlier base year has a larger effect on mitigation than the freeze year. Even if Indian emissions keep growing up to 2025, these have to be mitigated rapidly post 2025 to achieve the mitigation target of 15 percent of the base year value by 2050.

Figure 12: Mitigation potential and costs under an intermediate policy proposal

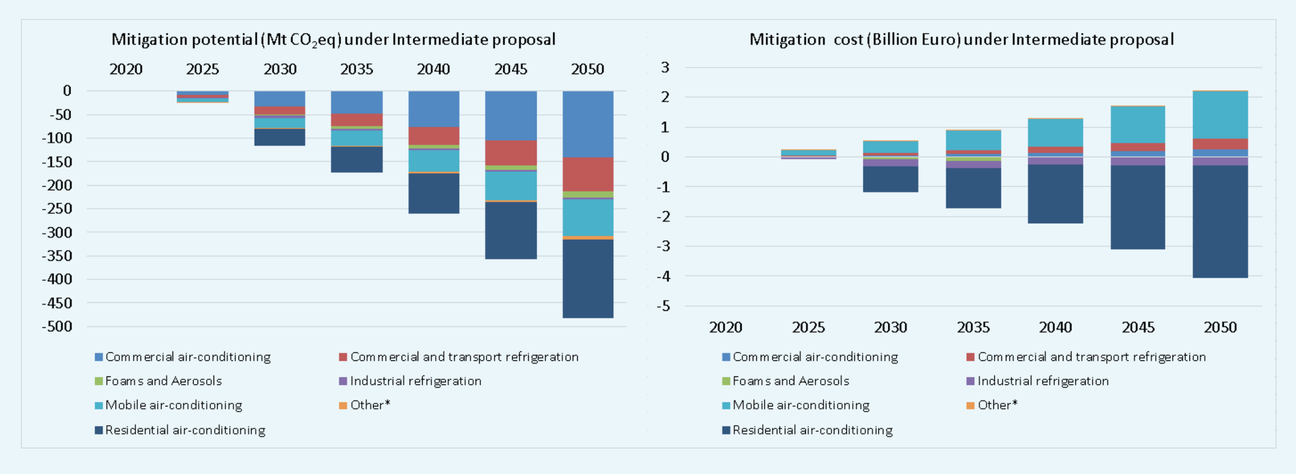
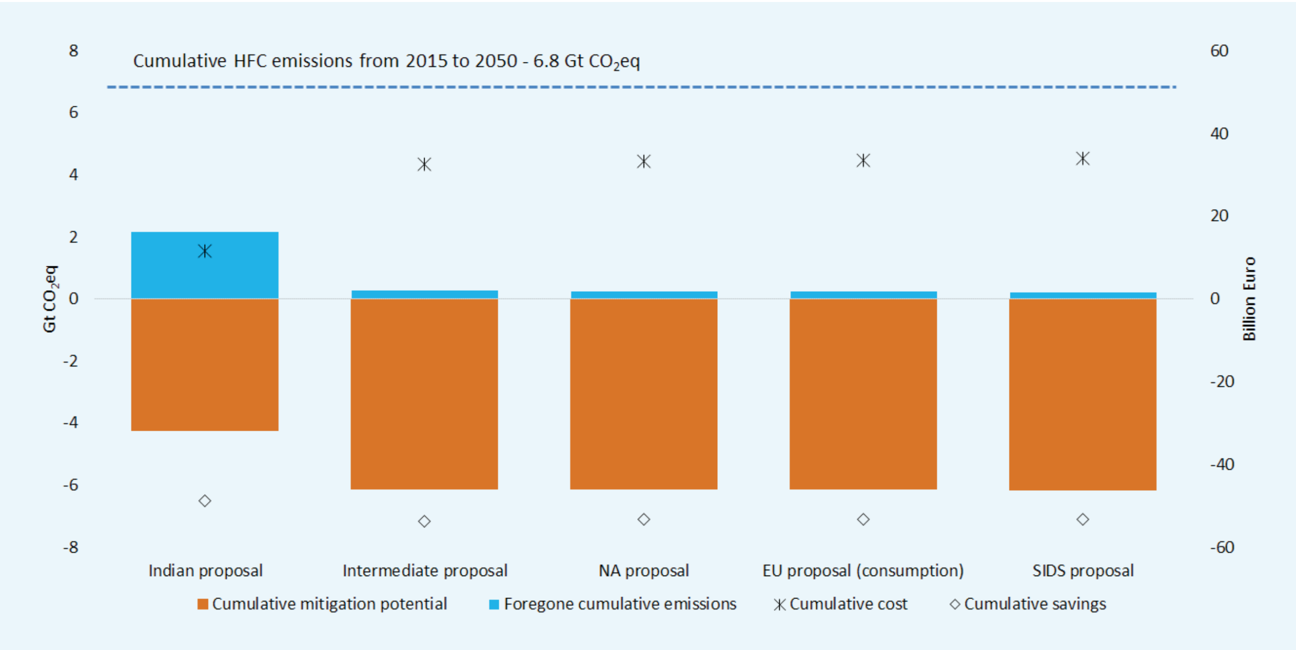


Figure 13 presents the cumulative HFC emissions and mitigation potential under different HFC phase-down scenarios in the period 2015 to 2050 at a marginal abetment cost of <200 Euro. The cumulative mitigation potential for India in the period 2015 to 2050 is estimated at ≥6 Gt CO_2eq in the NA, EU, and SIDS proposals, whereas it is estimated at 4.2 Gt CO_2eq in the Indian proposal. The reduction in cumulative emissions is less in the Indian proposal because of the later start of the controls for Article 5 parties as compared to those in other proposals. The cumulative mitigation potential in an intermediate proposal is also close to 6.1 Gt CO_2eq, which is approximately equivalent to the mitigation potential achieved through the NA, EU, and SIDS proposals due to the early base year, even if it comes with a seven-year grace period.

Figure 13: Cumulative mitigation potential, foregone cumulative emissions, and cumulative costs and saving under different HFC phase-down scenarios in the period 2015 to 2050



The mitigation potential that is attainable at a zero or negative marginal cost (see Section 4) is expected to be cost-effective. It is worth mentioning that while additional policy efforts are not assumed for negative-cost measures, such measures can provide key policy signals that can accelerate the transition to low-GWP or not-in-kind HFC alternatives. As different sectors will face different costs, we present both the positive and negative costs separately for the different proposals. The cumulative sum of the additional costs (undiscounted, in 2015 prices) in different HFC phase-down scenarios is also presented in Figure 13. The cumulative sum of the additional costs in different HFC phase-down scenarios is estimated at nearly 33–34 billion Euro in the NA, EU, SIDS, and intermediate proposals due to the different freeze-in years and baselines, as shown in Appendix IV. Table 6 presents the cumulative mitigation potential and costs in different HFC phase-down scenarios between 2015 and 2050. HFC phase-down (cumulative) costs are estimated at nearly 0.02 percent of India's expected cumulative GDP in the period 2015 to 2050 following the NA, EU, and SIDS proposals. At the same time, there are significant cost savings (53 billion Euro) primarily in the residential air-conditioning sector due to the lower cost of the alternative refrigerant (HC-290) as well as higher energy efficiency.

Table 6. Cumulative mitigation potential and costs in different HFC phase-down scenarios between 2015 and 2050

HFC phase-down proposals	Cumulative mitigation potential (Gt CO_2eq)	Foregone cumulative mitigation (Gt CO_2eq)	Cumulative cost (Billion Euro)	Cumulative savings (Billion Euro)	Annual emissions in 2050 (Mt CO_2eq)
NA proposal	6.14	0.25	33.24	-53.23	2.0
EU proposal	6.14	0.24	33.50	-53.28	2.4
SIDS proposal	6.16	0.22	34.03	-53.28	1.4
Indian proposal	4.23	2.16	11.59	-48.88	18.9
Intermediate proposal	6.11	0.28	32.60	-53.66	2.4

Note: - Costs are cumulative undiscounted costs and in terms of 2015 prices

-The maximum technically feasible mitigation potential is estimated at 6.4 Gt CO2eq for the period 2015–2050.

The cumulative mitigation cost of the Indian proposal is nearly one-third (11.6 billion Euro) as compared to those of the global proposals due to the later start of the controls for Article 5 parties as compared to those in the other proposals. The lower cost also reflects the lower mitigation undertaken under the Indian proposal. At the same time, there are significant cost savings (49 billion Euro) in the Indian proposal as well, primarily in the residential air-conditioning sector, due to the reasons mentioned earlier.

6. Uncertainty analysis

Our analysis is based on a range of assumptions regarding socio-economic growth, technical parameters, and HFC mitigation policy. It is critical to understand the range of uncertainties concerning our estimates. We discuss the following four kinds of uncertainties and describe how our results could change because of these factors.

6.1 Parametric uncertainties

There are two key variables that are defining and critical in terms of their impact on the estimates of HFC emissions—economic growth and leakage rates. The parametric uncertainties related to both these variables were tested in Chaturvedi et al. (2015). The average growth rate between 2010 and 2050 under the reference scenario was assumed to be 6.9 percent. Under the low-growth scenario, this was lowered to 5.5 percent. Compared to a total of approximately 503 Mt-CO_2eq HFC emissions in 2050 under the reference scenario, HFC emissions under the low-growth scenario are estimated to be 324 Mt-CO_2eq in 2050, 35 percent lower than the estimate under the reference scenario.

We tested higher and lower leakage rates across sectors compared to the leakage rate under the reference scenario. We found that in 2050, HFC emissions are likely to increase by 29 percent in the high-leakage rate scenario, and to decrease by 39 percent in the low-leakage rate scenario relative to the HFC emissions in the reference scenario.

6.2 Policy-induced uncertainty related to baseline and freeze years

Determining the baseline and freeze years is the most contentious issue in international negotiations on climate change. The NA, EU, and SIDS submissions propose early baseline and freeze years for Article 5 countries, as shown in Appendix IV, while the Indian submission proposes an average consumption of the 2028–30 as the baseline and 2031 as the freeze year. Thus, the proposals on the table already span a wide range. Our estimates of the mitigation potential and cost under the different proposals are hence not just estimates of the mitigation potential of different amendment proposals, but also of the uncertainty range due to the varying baseline and freeze years proposed. In addition to the proposals on the table, we also test an intermediate scenario, detailed in Section 5, where we test the sensitivity related to the freeze year by varying the freeze year and keeping the baseline as in the NA proposal. We find that if the baseline is based on a historical year, it does not matter much in terms of mitigation if we push the freeze year to a later date. Based on this one sensitivity test, we can say (although not strongly) that the impact of the baseline year on emission mitigation is more significant as compared to the freeze year. For drawing stronger conclusions, we will need to test different combinations of the baseline year and the freeze year. The freeze year is, however, important from the point of view of providing a strong policy signal to the market, to chemical producers, and to equipment manufacturers of the need to adjust their plans accordingly to meet the phase-down targets.

6.3 Uncertainty due to phase-down schedule

The NA and the SIDS proposals include a phase-down schedule for Article 5 countries. But the Indian and the EU proposals do not include a pre-specified phase-down schedule. The mitigation potential and cost for both these sets of proposals are based on an assumed phase-down schedule as specified in Appendix V. We also tested the sensitivity of our results to this assumption by modelling an alternative phase-down schedule for the Indian proposal. The details and mitigation results for the two phase-down schedule scenarios are given in Table 7.

Table 7. Sensitivity analysis using different phase-down schedules for the Indian proposal

Year	HFC phase-down steps		Annual Mitigation potential (Mt CO_2eq)		Annual Mitigation cost (Million Euro)	
	Existing	New	Existing	New	Existing	New
2035	100%	80%	60.9	84.2	0.0	36.9
2040	80%	60%	172.7	198.2	138.5	258.8
2045	40%	40%	322.2	322.2	683.7	683.7
2050	15%	15%	482.4	482.4	2,492.2	2,492.2

Note: - Costs are annual undiscounted costs and in terms of 2015 prices

Cumulative mitigation is estimated at 4.2 Gt CO_2eq in the existing schedule and at 4.5 Gt CO_2eq using the new HFC phase-down schedule. Similarly, cumulative mitigation cost is estimated at 11.6 billion Euro in the existing schedule and at 12.4 billion Euro using the new HFC phase-down schedule. As is evident from Table 7, our estimates of the mitigation potential are not sensitive to the assumption related to the phase-down schedule. As cost is closely aligned with the mitigation potential, the cost estimates are also not sensitive to the phase-down schedule.

6.4 Uncertainty related to refrigerant characteristics, refrigerant cost and system cost

Our results are contingent on the choice of refrigerants for different sectors, which is governed by the best available understanding of the feasibility of different alternatives available in different sectors. The alternatives that have been chosen are listed in the section on methodology and data. Two important points need to be highlighted here.

The first is related to the negative costs in the residential sector. The negative costs are due to the uptake of HC-290 for residential ACs. HC-290 is already being sold in the Indian and Chinese markets; nevertheless, other manufacturers have expressed concerns related to its flammability. This refrigerant, being a natural refrigerant, is cheaper as compared to R-410A, which is the refrigerant in the reference scenario. Also, it is highly energy efficient (Schwarz et al., 2011). Because of its higher energy efficiency and lower cost, the transition towards this refrigerant leads to significant savings for the residential AC sector. This result will hold if the residential AC market in India shifts to HC-290 in a big way. However, if there is another refrigerant that is low GWP, but is not as cost- effective (this is a high probability if it is a HFO) and not as energy efficient, the saving potential during the transformation in this sector could decline or go away altogether.

The second point is the mirror image of the first point. The current alternative for the mobile air-conditioning sector, which is most widely discussed in all forums, is HFO-1234yf. Given our current understanding and the way in which markets are shifting, this alternative appears to be the most feasible choice. However, the current cost of this refrigerant in India is 20 times the cost of HFC-134a, the refrigerant used in the reference scenario. Some Indian experts believe that the long-run price could be seven to eight times higher than HFC-134a due to application patents as well as the chemistry of this molecule. Our analysis is based on this assumption. Also, due to the expected lower energy efficiency of this refrigerant in Indian ambient conditions, additional expenditure will need to be incurred on modifying the heat exchanger unless the cooling system of the vehicle is redesigned. There will be additional plant and system level cost too which we have included. The high cost of transition across all proposals is largely due to the transition in the MAC sector. If in the future the cost of HFO-1234yf declines drastically, or there is an alternative refrigerant that satisfies all the technical criteria, yet is not as expensive as HFO-1234yf, the transition cost for this sector could come down significantly. Given the current understanding, however, such an alternative is not yet visible on the horizon. Updated information on system level cost could also change our numbers.

7. Conclusions and policy implications

This study presents estimates of current and future HFC emissions in India along with their technical mitigation potential and associated costs for the period 2010 to 2050. In the reference scenario, the use and emissions of HFCs grow rapidly in the coming decades. Initial results under the GAINS model indicate that in the reference scenario, which assumes no further adoption of legislative or voluntary incentives to control emissions than those currently in place, Indian HFC emissions are expected to grow by a factor of fifty between 2010 (10 Mt CO_2eq) and 2050 (503 Mt CO_2eq). In particular, a sharp increase in HFC emissions from air conditioning and refrigeration is expected. This will, in turn, be driven by a combined effect of the replacement of HCFCs with HFCs in accordance with the revised Montreal Protocol and an expected increase in demand for cooling services provided by refrigeration and air-conditioning appliances.

There are extensive opportunities to avoid potential HFC emissions by up to 98 percent primarily through replacement with existing alternative low-GWP substances. The results indicate that 37 percent of the mitigation potential in 2050 is expected to be attainable below 0 €/t CO_2eq, while 53 percent is expected to be attainable at a marginal cost between zero and 20 €/t CO_2eq. This is due to recently improved technology that allows for the use of low-cost alternative refrigerants (particularly in case of HCs) as replacement for HFCs. Hence, the mitigation potential is large and inexpensive, and is applicable to the residential air-conditioning, industrial refrigeration, and foam sectors, where a variety of inexpensive alternatives to HFCs (e.g., HCs, NH_3, and HFC-152a) are available. For commercial air-conditioning and refrigeration, the mitigation potential is high and relatively inexpensive as compared to mobile air-conditioning.

In the current legislation scenario, cumulative HFC emissions are estimated at 6.8 Gt CO_2eq in the period 2015 to 2050. The maximum technically feasible mitigation potential is estimated at 6.4 Gt CO_2eq for the same period. The objective of several existing national, regional, and global regulations is to limit the growth in future HFC use and emissions. At present, proposals have been submitted by North America (NA), the European Union (EU), the Small Island Developing (SID) regions, and India to amend the Montreal Protocol to substantially reduce growth in HFC use. Through the development of scenario projections for each of the proposed amendments to the Montreal Protocol, we estimate, by sector, the impact on long-term HFC emissions in India under the different amendments and in comparison with the existing regulations. For the scenario analysis, this study uses emissions instead of consumption to assess the mitigation costs. The scenario analysis indicates that a reduction of about 6.14–6.16 Gt CO_2eq cumulative HFC emissions is expected under the NA, EU, and SIDS proposals in the period 2015 to 2050. The reduction in cumulative emissions is less under the Indian proposal (nearly 4.2 Gt CO_2eq) because of the later start of the controls for developing countries than in the other three proposals. The cumulative mitigation cost of the Indian proposal is nearly one-third (11.6 billion Euro) as compared to global proposals (33–34 billion Euro) due to the later start of the controls for Article 5 parties as compared to other proposals. It may be noted that our results are contingent on the best available information on the availability and cost of low-GWP alternatives currently being discussed. Therefore, if new alternatives emerge for different sectors with different technical (i.e. removal efficiency, GWP, etc.) or cost characteristics as compared to the currently discussed alternatives, our quantified results and key insights may change significantly.

In terms of policy insights and actions, our analysis proposes two key action points as immediate steps. The first is the creation of a dedicated institutional structure for supporting R&D for low-GWP alternatives for different sectors and applications, particularly HC-290 for the room air-conditioning sector. Room air-conditioning is expected to be a high-growth sector, and currently there is only one low-GWP solution for this sector—HC-290. However, some sections of Indian industry are sceptical about the applicability of this refrigerant under all conditions, and have expressed concerns about safety. Our analysis shows that there is a huge opportunity for saving electricity through the adoption of this refrigerant. Strategic R&D is the only way that India can harness this opportunity during the transition. Second, Indian stakeholders need a better understanding of the cost of HFO-1234yf (which is being offered as a technically viable solution for the mobile air-conditioning sector) and the extent to which this cost can decline even in the long term. The current price of this refrigerant in the Indian market is 20 times that of HFC-134a, the refrigerant that is most widely used at present. This price should drop significantly in the long run. Still Indian experts believe that even in the long run, the price could be seven or eight times as much due to application patents as well as the chemistry of this molecule. Our analysis is based on this assumption. An in-depth analysis is required to understand the ways in which this potential cost could be reduced. If such an analysis finds that the potential long-term cost will not be seven to eight times, but only three times, then the estimated economic burden could be reduced by 15–20 percent (as the cost of the additional heat exchanger is also a big part of the additional cost). There would still be an additional economic burden. It is important to understand this and to find ways and strategies to minimise this burden.

The numbers emerging from our analysis are not set in stone and could change as our understanding of the underlying information changes. The two key points mentioned above highlight the strategies that are required to maximise the potential economic savings and to minimise the potential costs. A better understanding of both the issues will enable Indian policy makers to evaluate the trade-offs of the HFC phase-down and design measures to pursue domestic economic and social priorities as well as global environmental leadership.

The following additional policy implications can be drawn for India based on this study:

- The HFC phase-down in most sectors is likely to be a cost-effective way of complying with climate-policy targets as it affects a small number of sectors and has only moderate costs. In addition, switching to some cooling and insulation technologies without refrigerants ('not-in-kind' alternatives) can reduce not only HFCs, but also cut CO_2 emissions from energy consumption. Some of the mitigation potential in several sectors (i.e. in stationary air-conditioning, industrial refrigeration, etc.) is expected to come at a zero or negative marginal cost (i.e., at a marginal profit), which is an opportunity for India to take appropriate action.
- There are extensive opportunities to reduce HFC consumption and emissions in India. The results indicate that more than a third of the mitigation potential is attainable at zero or below zero marginal cost primarily due to inexpensive low-GWP alternatives and energy-efficiency benefits. Tracking energy-efficiency opportunities is in India's self-interest, and the adoption of appropriate domestic policies can help achieve and accelerate the transition to low-GWP and not-in-kind alternatives. Therefore, adequate domestic policy measures are required to increase incentives and to ensure the adoption of regulations for more energy-efficient appliances in the phase-out of HCFCs and the phase-down of HFCs.
- At the sectoral level, applications using HFCs (except HFC-134a used primarily in mobile ACs and domestic refrigerators) are currently still at an early stage in India. Further, in many consuming sectors, low-GWP or zero-GWP substitutes and technologies are already commercially available. However, there are currently no domestic regulations on HFCs in India. In the absence of regulations on HFC use, India should focus on good practices like leakage control, adoption of improved components, and end-of-life recollection. India's amendment proposal already signals its intent to phase-down high-GWP HFCs in the long run.

- As we are interested in estimating the costs of the additional policy efforts needed to attain the required emission-reduction targets, we present negative and positive abatement costs separately. Due to the different freeze-in years and baselines, the cumulative costs in different HFC phase-down scenarios are estimated at nearly 33–34 billion Euro in the NA, EU, SIDS, and intermediate proposals, that is, approximately 0.02 percent of India's expected cumulative GDP from 2015 to 2050. At the same time, there are significant cost savings (53 billion Euro) primarily in the residential air-conditioning sector due to the lower cost of the alternative refrigerant (HC-290) as well as higher energy efficiency.
- The cumulative mitigation cost of the Indian proposal is nearly one-third (11.6 billion Euro) as compared to those of the global proposals due to the later start of the controls for Article 5 parties as compared to those of the other proposals. The lower cost also reflects the lower mitigation undertaken under the Indian proposal. At the same time, there are significant cost savings (49 billion Euro) under the Indian proposal as well, primarily in the residential air-conditioning sector, due to the reasons mentioned earlier.
- A phase-down of HFCs is likely to be a cost-effective option for India if it is to contribute to the global climate target that limits temperature increase to 2 °C above pre-industrial levels. As the world's fourth largest GHG emitter, India's active participation in the phase-down of HFCs will help to meet its current *pledge* to improve the emissions intensity of its GDP by *33* to *35 percent* by 2030 below 2005 levels in a cost-effective manner. However, the cost-effectiveness here needs to be understood in the context of competing GHG-mitigation options like solar energy and energy efficiency. This is an area for future research.
- HFCs are the low-hanging fruit in tackling climate change. Amending the Montreal Protocol provides developing countries like India proven tools and support mechanisms that work within an already established and functioning framework. In the end, the issue of HFCs must be addressed effectively and meaningfully if we are to move forward on climate change.

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Appendix I

GAINS India – regions*

**ANPR: Andhra Pradesh (including Telangana); ASSA: Assam, BIHA: Bihar; CHHA: Chhattisgarh; DELH: Delhi; GOA: Goa; GUJA: Gujarat; HARY: Haryana; HIPRL: Himachal Pradesh; WHIM: Jammu and Kashmir; JHAR: Jharkhand; KARN: Karnataka; KERA: Kerala (including Lakshadweep); MAPR: Madhya Pradesh; MAHA: Maharashtra (including Daman and Diu, Dadra and Nagar Haveli); EHIM: including Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim, Tripura; ORIS: Odisha; PUNJ: Punjab; RAJA: Rajasthan; TAMI: Tamil Nadu (including Andaman and Nicobar Islands, Pondicherry); UTPR: Uttar Pradesh; UTAN: Uttarakhand; BENG: West Bengal*

Appendix II

Mitigation options for HFC emissions considered in the GAINS model

Sector description	Technology description
Aerosols	Alternative hydrocarbon propellant (i.e. propane (HC-290), iso-butane (HC-600a), n-propane, etc.)
	Alternative propellant (i.e. HFC-152a)
	Alternative propellant (e.g. HFO-1234ze)
Commercial air conditioning, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative hydrocarbon refrigerant (i.e. propane, iso-butane, propene (HC-1270), etc.)
	Alternative technology: pressurised CO_2
	Alternative low-GWP HFCs (e.g. HFC-152a)
	Alternative low-GWP refrigerant (i.e. HFO-1234yf)
Commercial air conditioning, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative hydrocarbon refrigerant (i.e. propane, iso-butane, propene, etc.)
	Alternative technology: pressurised CO_2
	Alternative low-GWP HFCs (e.g. HFC-152a)
	Alternative low-GWP refrigerant (i.e. HFO-1234yf)
Commercial refrigeration, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative hydrocarbon refrigerants (i.e. propane, iso-butane, propene, etc.)
	Alternative low-GWP HFCs (e.g. HFC-152a)
	Alternative technology: pressurised CO_2
Commercial refrigeration, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative hydrocarbon refrigerants (i.e. propane, iso-butane, propene, etc.)
	Alternative low-GWP HFCs (e.g. HFC-152a)
	Alternative technology: pressurised CO_2
Domestic small hermetic refrigerators, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative hydrocarbon refrigerant (i.e. iso-butane)
Fire extinguishers, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative agent: Fluoro-ketone (FK-5-1-12)
Fire extinguishers, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative agent: Fluoro-ketone (FK-5-1-12)
Ground source heat pumps, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative hydrocarbon refrigerants (i.e. propane (HC-290), propene (HC-1270), etc.)
	Alternative technology: pressurised CO_2
	Alternative low-GWP HFCs (e.g. HFC-152a)
Ground source heat pumps, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative hydrocarbon refrigerants (i.e. propane (HC-290), propene (HC-1270), etc.)
	Alternative technology: pressurised CO_2
	Alternative low-GWP HFCs (e.g. HFC-152a)
HCFC-22 production for emissive use	Post combustion of HFC-23
HCFC-22 production for feedstock use	Post combustion of HFC-23

Sector description	Technology description
Industrial refrigeration (including food and agricultural sectors), emissions banked in equipment	Good practice: leakage control, improved components
	Alternative refrigerant: propane (HC-290)
	Alternative low-GWP HFCs (e.g. HFC-152a)
	Alternative refrigerant: ammonia (NH_3)
	Alternative technology: pressurised CO_2
Industrial refrigeration (including food and agricultural sectors), emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative refrigerant: propane (HC-290)
	Alternative low-GWP HFCs (e.g. HFC-152a)
	Alternative refrigerant: ammonia (NH_3)
	Alternative technology: pressurised CO_2
Mobile AC in buses, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative refrigerant: HFO-1234yf
	Alternative technology: pressurised CO_2
Mobile AC in buses, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative refrigerant: HFO-1234yf
	Alternative technology: pressurised CO_2
Mobile AC in heavy-duty trucks, emissions banked in equipment	Good practice: end-of-life recollection
	Alternative refrigerant: HFO-1234yf
	Alternative technology: pressurised CO_2
Mobile AC in heavy-duty trucks, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative refrigerant: HFO-1234yf
	Alternative technology: pressurised CO_2
Mobile AC in cars, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative refrigerant: HFO-1234yf
	Alternative technology: pressurised CO_2
Mobile AC in cars, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative refrigerant: HFO-1234yf
	Alternative technology: pressurised CO_2
Mobile AC in light-duty trucks, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative refrigerant: HFO-1234yf
	Alternative technology: pressurised CO_2
Mobile AC in light-duty trucks, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative refrigerant: HFO-1234yf
	Alternative technology: pressurised CO_2
One-component foams	Alternative hydrocarbon blowing agents (i.e. Iso-butane (HC-600a), Iso-pentane, n-pentane, etc.)
	Alternative technology: pressurised CO_2
	Alternative blowing agent: HFO-1234ze
	Alternative low-GWP HFCs (e. g. HFC-152a)
Other foams	Alternative hydrocarbon blowing agents (i.e. Iso-butane (HC-600a), Iso-pentane, n-pentane, etc.)
	Alternative technology: pressurised CO_2
	Alternative blowing agent: HFO-1234ze
	Alternative low-GWP HFCs (e.g. HFC-152a)
Other HFC use	Alternative low-GWP HFCs (e.g. HFC-152a)

Sector description	Technology description
Refrigerated transport, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative hydrocarbon refrigerant: propane (HC-290), propene (HC-1270)
	Alternative technology: pressurised CO_2
	Alternative low-GWP HFCs (e.g. HFC-152a)
Refrigerated transport, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative hydrocarbon refrigerant: propane (HC-290), propene (HC-1270)
	Alternative technology: pressurised CO_2
	Alternative low-GWP HFCs (e.g. HFC-152a)
Residential air conditioning, emissions banked in equipment	Good practice: leakage control, improved components
	Alternative hydrocarbon refrigerant (i.e. propane (HC-290), iso-butane (HC-600a), propene (HC-1270), etc.)
	Alternative technology: pressurised CO_2
	Alternative low-GWP HFCs (e.g. HFC-152a)
	Alternative low-GWP refrigerant (i.e. HFO-1234yf)
Residential air conditioning, emissions from scrapped equipment	Good practice: end-of-life recollection
	Alternative hydrocarbon refrigerant (i.e. propane (HC-290), iso-butane (HC-600a), propene (HC-1270), etc.)
	Alternative technology: pressurised CO_2
	Alternative low-GWP HFCs (e.g. HFC-152a)
	Alternative low-GWP refrigerant (i.e. HFO-1234yf)
Solvents	Ban of use

Appendix III

Market price of current and alternative refrigerants

To avoid use and to reduce emissions of both hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs), a variety of climate-friendly, energy-efficient, safe, and proven alternatives are available today. However, leapfrogging away from HCFCs/HFCs to low-GWP or natural alternatives will entail costs. In the last few years, several low-GWP alternatives have become available, offering developing countries an opportunity to transition directly from HCFCs to cost-effective, low-GWP alternatives. For example, low-GWP alternatives to HCFCs/HFCs are economically viable for room ACs in India. The Indian market has some of the leading players in the transition to low-GWP refrigerants in ACs, with Daikin establishing its first developing-country HFC-32 factory in India (capacity 1 million units) and reporting sales of 150,000 such units. Similarly, Godrej & Boyce are leading the way in the manufacturing of HC-290 ACs in India, reporting sales of 100,000 units since 2013 (NRDC et al., 2013).

Table A.1 presents the market prices of current and alternative refrigerants as assumed in our study, which have also been verified through interaction with industry experts. The long-term price of HFC-32 is assumed to be the same as that of R-410A based on inputs from Daikin India. The R-410A price is based on inputs from ISHRAE and other industry experts. Further, the HFC-404A or R-404A prices are assumed to be the same as those for R-410A, and this assumption is consistent with the findings of the UNEP/TEAP (2012) report. The market prices for HFC-134a and HC-600a have been verified with information from Whirlpool India. The market prices of various hydrocarbon (HC) coolants differ marginally, and the HC-290 price is assumed to be the same as that for HC-600a. Carbon dioxide ($CO_{2)}$ and ammonia (NH_3) prices are taken from the UNEP/TEAP (2012) report and have also been verified through interaction with industry experts. HFO-1234yf prices are calculated based on inputs from Subros India, Tata Motors, and ISHRAE, which suggest that the price could be anywhere between six and ten times the price of HFC-134a. The HFO-1234ze price is taken from the UNEP/TEAP (2012) report and is also verified through interaction with industry experts.

Table A.1: Market price of current and alternative refrigerants

Refrigerant	Market price (Euro*/kg)	Reference
HFC-32, R-410A, HFC-404A	7.1	Inputs received from Daikin India, ISHRAE, and other industry experts; UNEP/TEAP (2012)
HC-290, HC-600a	6.0	Inputs received from Whirlpool India and other industry experts
HFC-134a	5.2	
NH_3	1.6	UNEP/TEAP (2012)
CO_2	1.6	
HFO-1234ze	40.0	
HFO-1234yf	41.7	Inputs received from Tata Motors, Subros India, ISHRAE, and corroborated with US-EPA (2013).

**1€ = ₹70*

Note: This table gives the refrigerant cost, which is only a part of the total incremental cost. The total incremental cost including system cost is what matters for our analysis.

In this study, refrigerant prices mentioned in Table A.1 are adjusted for equipment/appliance charge rates and form a component of the refrigerant cost (initial refrigerant charge at the factory) of the control options. Based on comparisons of HFC-32 and R-410A room air-conditioner models from Daikin brochures, the hardware cost of the HFC-32-based AC is 9 percent lower than that of the R-410A-based room AC. The investment cost for the propane (HC-290)-based room AC is higher than that of the existing HCFC-22 unit, but is assumed to be the same as that of the R-410A reference unit. It is assumed that the cost of safety provisions in the HC-290 unit is offset by the lower material requirements compared to R-410A and hence results in zero incremental investment cost (Table A.2).

Table A.2. Market price and O&M cost of room air-conditioners in Indian market

Refrigerant	Lifetime of equipment (years)	Investment cost (€/activity)	Annual O&M cost[8] (€/activity)	Electricity use (%)
Baseline (R-410A*)	10	637.6	10.4	
Alternative low-GWP HFCs (i.e. HFC-32)		582.0[9]	7.5	-6%[10]
Alternative hydrocarbon (i.e. HC-290)		637.6	4.6	

**Currently in use for room ACs in Indian market.*

Efficiency gains are considered to be 6 percent for the HFC-32 unit. In the absence of testing results, over a complete range of ambient temperatures in India, or any industry inputs, efficiency gains from HC-290 are considered the same as that from HFC-32, i.e. 6 percent. The refrigerant refill cost forms a part of the O&M cost of control technologies and is based on operational leakages. Hence, the servicing demand of end-use equipment then depends on the number of recharges that will be required over the lifetime of the equipment (Chaturvedi et al., 2015). HC or HC mixes utilised in the domestic refrigerator industry contribute 3–4 percent of the incremental cost per domestic refrigerator unit, and energy requirements decrease by 1.5 percent in HC-based refrigerators. Contributions of refrigerant prices to fixed investment cost and O&M cost are calculated in a similar manner as described above for residential ACs.

8 It is assumed that there is no change in the labour cost of refilling the equipment with current and alternative refrigerants in use.
9 Cost inputs provided by Daikin India.
10 6 percent efficiency gain for HFC-32-based single-split room air-conditioner as per Daikin India.

Appendix IV

HFC phase-down schedules for Article 5 and non-Article 5 parties

Key elements	North American proposal	European Union proposal	Indian proposal	Small Island Developing States (SIDS) proposal	African group non-paper
Listing of HFCs	19 HFCs in one annex divided into two groups	19 HFCs in one annex divided into two groups	19 HFCs in two annexes divided into five groups	22 HFCs (including three HFOs) in one annex divided into two groups	21 HFCs (including two HFOs) in one annex divided into two groups
Non-Article 5 Measures					
Control period/ length	2019–2036 (17 years)	2019–2034 (15 years)	2016–2035 (19 years)	2017–2033 (16 years)	To be determined
Control measures for HFC production and consumption (% of baseline)	2019 – 90% 2024 – 65% 2030 – 30% 2036 – 15%	2019 – 85% 2023 – 60% 2028 – 30% 2034 – 15%	2016 – 100% 2018 – 90% 2023 – 65% 2029 – 30% 2035 – 15%	2017 – 85% 2021 – 65% 2025 – 45% 2029 – 25% 2033 – 10%	To be determined[11]
Baseline (GWP–weighted)	100% of HFCs + 75% of HCFC consumption and production (averaged from 2011–2013)	100% of HFCs + 45% of HCFC consumption and production (averaged from 2009–2012)	100% of HFCs averaged from 2013–2015 + 25% of the 1989 HCFC base level for the HCFC phase-out	100% of HFCs averaged from 2011–2013 + 10% of 1989 HCFC base level for the HCFC phase-out	Baseline to be determined
Article 5 Measures					
Grace period (beyond beginning of non-Article 5 control period)	5 years	None	15 years	7 years	Grace period to be determined
Control period/ length	2021–2046 (25 years)	2019–2040 (21 years)	2031–2050 (19 years)	2020–2040 (20 years)	To be determined
Control measures for HFC production and consumption (% of baseline)	2021 – 100% 2026 – 80% 2032 – 40% 2046 – 15%	*Consumption:* 2019 – 100% *Production:* 2019 – 100% 2040 – 15% Further and intermediate steps agreed by 2020	2031 – 100% 2050 – 15% National phase-down steps are to be decided 5 years in advance for the next 5-year period	2020 – 85% 2025 – 65% 2030 – 45% 2035 – 25% 2040 – 10%	Schedule to be determined
Baseline (GWP–weighted)	100% of HFCs + 50% of HCFCs consumption and production (averaged from 2011–2013)	*Production:* 100% of HFCs + 70% of HCFC (averaged from 2009–2012) *Consumption:* Base level: 100% of HFCs + 100% of HCFCs (averaged from 2015–2016)	100% of HFCs averaged from 2028–2030 + 32.5% of HCFC base level (2009–2010 average) for the HCFC phase-out	100% of HFCs averaged from 2015–2017 + 65% of HCFC base level (2009–2010 average) for the HCFC phase-out	Baseline to be determined
Multilateral fund financing	Agreed incremental costs	Agreed incremental costs	Full conversion and where transitional technologies are deployed, second conversion costs starting at beginning of control period	Agreed full incremental costs starting in advance of control period	Sufficient, unconditional support
Sponsor's estimate of HFC emissions reduction by 2050	90–112 billion metric tonnes CO_2eq.	79 billion metric tonnes CO_2eq.	Unspecified	Unspecified	Unspecified

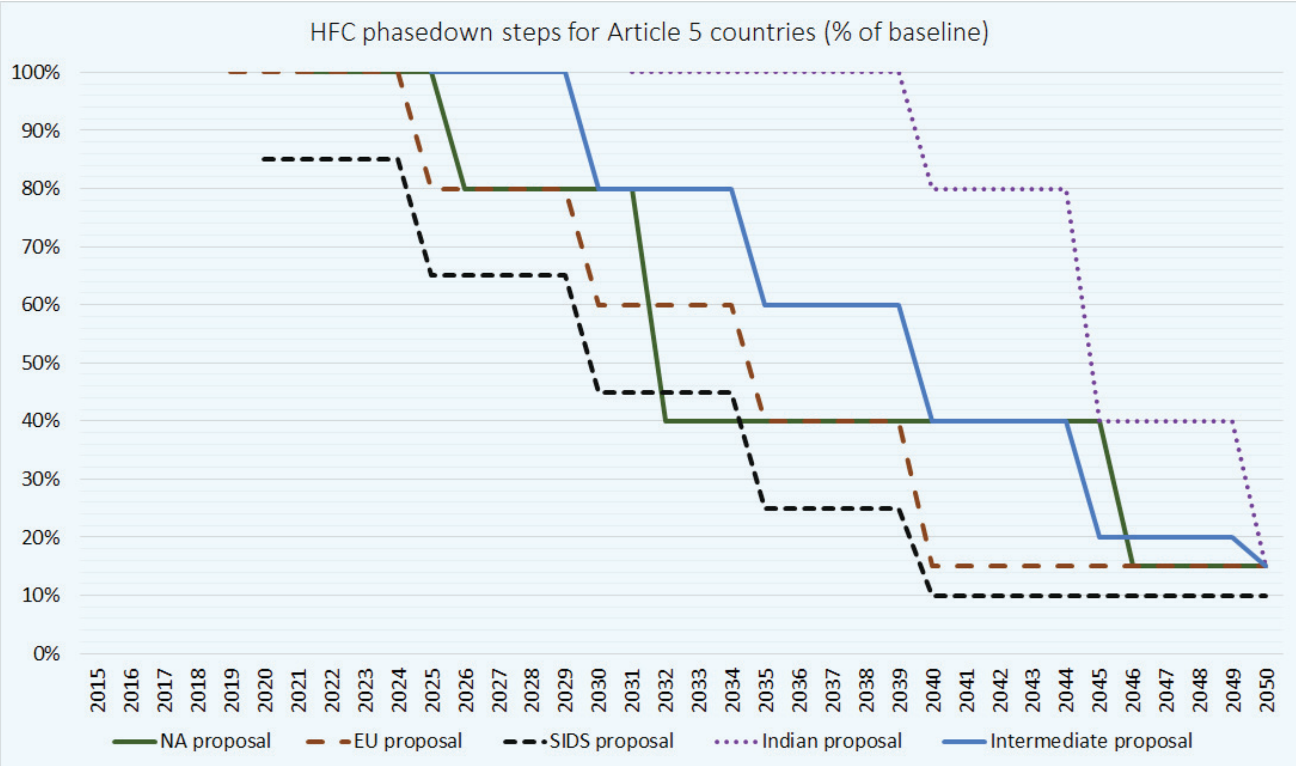
11 Schedule to be determined based on TEAP study on technology availability, cost, safety, energy efficiency, and environmental considerations.

Key elements	North American proposal	European Union proposal	Indian proposal	Small Island Developing States (SIDS) proposal	African group non-paper
Impact on KP/ UNFCCC	Complementary, with continued HFC emissions reporting	Complementary, with continued HFC emissions reporting	Complementary, with continued HFC emissions reporting	Complementary, with continued HFC emissions reporting	Complementary
Import/export licensing	Yes	Yes	Yes	Yes	Unspecified
Relationship to HCFC phase-down	Does not alter HCFC schedule	Does not alter HCFC schedule	Does not alter HCFC schedule	Does not alter HCFC schedule	Unspecified
Further review and exceptional provisions	Technology reviews to evaluate availability of alternatives	No	Continued use of transitional HFCs and HFC blends where low- [[GWP options do not yet exist	No	Exceptional measures for countries with high ambient temperatures
Allocation of imported HFCs	Unspecified	Importing party responsible for consumption	Unspecified	Unspecified	Unspecified
Controls HFC-23 by-product emissions	Yes	Unspecified	No, but proposes comprehensive R&D efforts to find feedstock and process agent uses and thus minimize emissions	Yes	Unspecified
Bans HFCs trade with non-parties to the amendment	Yes	Yes	Yes	Yes	Unspecified

Source: UNEP, 2015a–d; Jaiswal et al. 2015.

Appendix V:

HFC phase-down steps for Article 5 countries



Appendix VI

Removal efficiency and cost parameters considered in the GAINS model

Sector description	Technology description	Unit of activity data	Removal efficiency	Cost parameters per unit of activity data: Lifetime of equipment years	Investment (million €)	Operation & maintenance (million €/year)
Aerosols	Alternative hydrocarbon propellant (i. e. propane (HC-290), iso-butane (HC-600a), n-propane etc.)	kt HFC	-99.79%	n.a.	0	-2
	Alternative propellant (i. e. HFC-152a)		-91.33%	n.a.	0	-1
	Alternative propellant (e. g. HFO-1234ze)		-99.58%	n.a.	0	9.3
Commercial air conditioning, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-30%	n.a.	0	15.6
	Alternative hydrocarbon refrigerant (i. e. propane, iso-butane, propene (HC-1270), etc.)		-99.75%	20	34.9	-1.9
	Alternative technology: pressurized CO_2		-99.95%	20	124.8	-1.4
	Alternative low-GWP HFC's (e. g. HFC-152a)		-93.37%	20	138.3	-0.7
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	20	47.1	10.4
Commercial air conditioning, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-88%	n.a.	0	16.7
	Alternative technology: pressurized CO_2		-99.95%	n.a.	0	0.0
Commercial refrigeration, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-67%	10	0	9.1
	Alternative hydrocarbon refrigerants (i. e. propane, iso-butane, propene, etc.)		-99.92%	10	913.5	-0.9
	Alternative low-GWP HFC's (e. g. HFC-152a)		-94.43%	10	136.9	-12.7
	Alternative technology: pressurized CO_2		-99.96%	10	757.6	-0.7
Commercial refrigeration, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	n.a.	0	9.1
	Alternative technology: pressurized CO_2		-99.96%	n.a.	0	0
Domestic small hermetic refrigerators, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	n.a.	0	0.8
	Alternative hydrocarbon refrigerant (i. e. iso-butane)		-99.79%	15	150	0
HCFC-22 production for emissive use	Post combustion of HFC-23	kt HFC	-0.95%	10	16.5	2.2
HCFC-22 production for feedstock use	Post combustion of HFC-23		-0.95%	10	16.5	2.2
Industrial refrigeration (including food and agricultural sectors), emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-42%	n.a.	0	1.1
	Alternative low-GWP HFC's (e. g. HFC-152a)		-95.01%	15	136.9	-12.7
	Alternative refrigerant: ammonia (NH_3)		-100%	15	468.1	-77.0
	Alternative technology: pressurized CO_2		-99.96%	15	133.6	0.0
Industrial refrigeration (including food and agricultural sectors), emissions	Good practice: end-of-life recollection	kt HFC	-88%	n.a.	0	1.1
	Alternative technology: pressurized CO_2		-99.96%	n.a.	0	0
Mobile air-conditioner in buses, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	n.a.	0	1.9
	Alternative refrigerant: HFO-1234yf		-99.72%	20	117.5	11.0
	Alternative technology: pressurized CO_2		-99.93%	20	863.0	-1.09
Mobile air-conditioner in buses, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	n.a.	0	17.4
	Alternative technology: pressurized CO_2		-99.93%	n.a.	0	0
Mobile air-conditioner in heavy duty trucks, emissions banked in equipment	Good practice: end-of-life recollection	kt HFC	-50%	n.a.	0	1.9
	Alternative refrigerant: HFO-1234yf		-99.72%	20	38.4	11.0
	Alternative technology: pressurized CO_2		-99.93%	20	114.5	-1.09
Mobile air-conditioner in heavy duty trucks, emissions from scrapped	Good practice: end-of-life recollection	kt HFC	-80%	n.a.	0	17.4
	Alternative technology: pressurized CO_2		-99.93%	n.a.	0	0
Mobile air-conditioner in cars, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	n.a.	0	1.9
	Alternative refrigerant: HFO-1234yf		-99.72%	12	199.8	9.1
	Alternative technology: pressurized CO_2		-99.93%	12	249.7	-5.9
Mobile air-conditioner in cars, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	n.a.	0	17.4
	Alternative technology: pressurized CO_2		-99.93%	n.a.	0	0
Mobile air-conditioner in light duty trucks, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	n.a.	0	1.9
	Alternative refrigerant: HFO-1234yf		-99.72%	20	38.6	11.0
	Alternative technology: pressurized CO_2		-99.93%	20	126.9	-1.09
Mobile air-conditioner in light duty trucks, emissions from scrapped	Good practice: end-of-life recollection	kt HFC	-80%	n.a.	0	17.4
	Alternative technology: pressurized CO_2		-99.93%	n.a.	0	0
One component foams	Alternative hydrocarbon blowing agents (i. e. Iso-butane (HC-600a), Iso-pentane, n-pentane, etc.)	kt HFC	-99.74%	15	1.7	0
	Alternative technology: pressurized CO_2		-99.91%	15	7	-1
	Alternative blowing agent: HFO-1234ze		-99.47%	15	3.5	7
	Alternative low-GWP HFC's (e. g. HFC-152a)		-89.13%	15	1.7	-3
Other foams	Alternative hydrocarbon blowing agents (i. e. Iso-butane (HC-600a), Iso-pentane, n-pentane, etc.)	kt HFC	-99.74%	15	1.7	0
	Alternative technology: pressurized CO_2		-99.91%	15	7	-1
	Alternative blowing agent: HFO-1234ze		-99.47%	15	3.5	7
	Alternative low-GWP HFC's (e. g. HFC-152a)		-89.13%	15	1.7	-3
Other HFC use	Alternative low-GWP HFC's (e. g. HFC-152a)	kt HFC	-91.33%	n.a.	0	2
Refrigerated transport, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-20%	n.a.	0	16.2
	Alternative hydrocarbon refrigerant: Propane (HC-290), propene (HC-1270)		-99.85%	15	1134.6	-8.3
	Alternative technology: pressurized CO_2		-99.95%	15	737.3	-5.6
	Alternative low-GWP HFC's (e. g. HFC-152a)		-93.45%	15	136.9	-12.7
Refrigerated transport, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	n.a.	0	16.2
	Alternative technology: pressurized CO_2		-99.95%	n.a.	0.0	0.0
Residential air conditioning, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-30%	n.a.	0.0	3.3
	Alternative hydrocarbon refrigerant (i. e. propane (HC-290), iso-butane (HC-600a), propene (HC-1270), etc.)		-99.85%	10	0.0	-2.4
	Alternative technology: pressurized CO_2		-99.95%	10	116.8	17.9
	Alternative low-GWP HFC's (e. g. HFC-32)		66.25%	10	-108.6	-0.6
	Alternative low GWP refrigerant (i. e. HFO-1234yf)		-99.80%	10	87.6	2.3
Residential air conditioning, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-88%	n.a.	0	33.3
	Alternative technology: pressurized CO_2		-99.95%	n.a.	0	0
Solvents	Ban of use	kt HFC	-100%	0	0	1
Railway air-conditioners, emissions banked in equipment	Good practice: leakage control, improved components	kt HFC	-50%	n.a.	0	1.9
	Alternative refrigerant: HFO-1234yf		-99.72%	12	68.6	6.7
	Alternative technology: pressurized CO_2		-99.93%	12	2139.2	-1.46
Railway air-conditioners, emissions from scrapped equipment	Good practice: end-of-life recollection	kt HFC	-80%	n.a.	0	1.9
	Alternative technology: pressurized CO_2		-99.93%	n.a.	0	0

Note: The investment cost given in the table above includes refrigerant cost as well as physical system cost. For example, for the car air-conditioning sector, incremental cost of HFO-1234yf over HFC-134a (including refrigerant and system cost) has been assumed to be 80 Euros (Rs 5600) per car across the lifetime of a car. Given the average charge size of 400 grams for a car, this translates to 200 Euros/kg one time investment cost which is given in the table. The investment cost given here should not be read as the cost of refrigerant.

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