Council on Energy,
Environment and Water

July 2014 | New Delhi, India

CEEW Working Paper 2014/7

Modelling Long Term HFC Emissions from India's Residential Air-Conditioning Sector

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Modelling Long Term HFC Emissions from India's Residential Air-Conditioning Sector:

Exploring Energy and Global Warming Implications of Transition to Alternative Refrigerants, Implementation of Best Practices, and Adoption of a Sustainable Lifestyle

CEEW Working Paper July 2014 ceew.in

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ABOUT THE AUTHORS

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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 graduated from Technical University of Denmark-DTU with Master of Science (engineering) 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. Prior to his master, he has close to two years of work experience in process industry. Mohit holds a degree in Chemical Engineering from Malaviya National Institute of Technology. Before joining CEEW, Mohit has briefly volunteered for CSE to prepare framework for national energy modelling.

ABSTRACT

India's growing role in the global climate debate makes it imperative to analyse emission reduction policies and strategies across range of greenhouse gases, especially for under researched non-CO_2 gases. Hydrofluorocarbons (HFCs) are high global warming potential (GWP) non-CO_2 short-lived climate forcers. HFC usage in cooling equipment and subsequent emissions are expected to increase dramatically in India with the phase out of hydrochlorofluorocarbons (HCFCs) as coolants in air-conditioning equipment. We focus on the residential air conditioner (AC) sector in India and analyse a suite of HFC and alternative coolant gas scenarios for understanding the implications for GHG emissions from this sector. We find that if unabated, HFC410A emissions will contribute to 32% of the total global warming impact from the residential AC sector in India in 2050, irrespective of future economic growth trajectory, rest 68% is from energy to power residential ACs.

A move towards more efficient, low GWP alternative refrigerants will significantly reduce the global warming footprint of this sector by 31-38% during the period 2010-50, due to gains both from energy efficiency as well as low GWP alternatives. Best practices for reducing direct emissions are important but only of limited utility, and if a sustainable lifestyle is adopted by consumers with lower floorspace, low GWP refrigerants, and higher building envelop efficiencies, cumulative emissions during 2010-50 can be reduced by 46% compared to the Reference scenario. We conclude by highlighting that there undoubtedly is a need to move away from high GWP refrigerants towards alternative gases. Additionally we also show that energy efficiency improvements achieved during this transition will have a significant effect on reducing the indirect emissions from this growing sector. This analysis is particularly timely because Amendments are proposed to control HFC production and consumption under the Montreal Protocol as a complement to the current control of HFC emissions under the Kyoto Protocol.

POLICY HIGHLIGHTS

- HFC 410A emissions will have a significant contribution in GHG emissions from the residential AC sector, and there undoubtedly needs to be a move away from this gas towards alternative gases. The government should give a strong signal to the market that this transformation is going to happen sooner or later.
- The energy efficiency potential of end use AC technologies needs to be harnessed. Bureau of Energy Efficiency (BEE) and other relevant government authorities should analyse the reason for low penetration of high efficiency equipment and take steps to increase their market share. BEE should have more standardized testing procedures for high ambient conditions and more testing facilities.
- Building efficiency improvements can reduce the cooling energy demand significantly, and BEE should extend building energy conservation codes policy to the residential sector immediately.
- Information on AC coolant recharge frequency and recovery of scrapped AC units is required for better estimation and understanding of direct emissions. Government authorities should set guidelines and mandate reporting of data for this purpose. Authorities also need to regulate/incentivize recovery and re-use of high global warming potential AC coolant.
- For contentious issues where there is no consensus within the industry, like flammability of any particular alternative refrigerant, the government needs to undertake an independent technical assessment that can provide unbiased and reliable information to the market for making optimal choices suitable for individual manufacturers.

1. INTRODUCTION

Global warming is arguably debated as the most critical challenge being faced by policy makers and communities around the world. Impacts of global warming on ecosystems and social-systems are already being experienced and this will only intensify in the future if governments fail to limit the emission and accumulation of greenhouse gases (GHGs) in the atmosphere (IPCC, 2014). A large body of research has focused on the global GHG emission mitigation challenge. Policies and strategies for mitigating emissions have been analyzed and debated for both the supply side through decarbonisation of energy supply systems, as well as on the demand side through either energy efficiency measures or through alternative approaches that lead to decreased reliance on fossil energy (Chapman, 2007; Escobar et al., 2009; Odenberegr et al., 2009; Doi et al., 2011; Thomson et al., 2011; Clarke et al., 2012; Eom et al., 2012; Shukla and Chaturvedi, 2012; William et al., 2012; Chaturvedi and Shukla, 2013; The World Bank, 2013; Chaturvedi and Kim, 2014).

However, it can be concluded from the available literature that a large part of existing climate policy research has focused on carbon dioxide emission pathways and the carbon emission mitigation challenge (IPCC. 2007; Clarke et al., 2009; GEA, 2012; Calvin et al., 2012; IPCC, 2014; Kriegler et al., 2014). Research on other potent GHGs is available (Klimont et al., 2009; Velders et al., 2009; Gschrey et al., 2011; Hoeglund-Isaksson , 2012; Smith and Mizrahi, 2013; Rose et al., 2013), but arguably has been given less attention than it deserves. The importance of non-CO2 GHGs has been highlighted by Hu et al. (2013), who show that mitigation of short-lived climate polluters can decrease the sea level rise rate by 24-50%. This is true even more so for rapidly developing emerging economies where most of the policy discussions are focused on development issues and how to align carbon mitigation policies with sustainable economic development pathways.

Hydrofluorocarbons (HFCs) are one of six greenhouse gases controlled under the Kyoto Protocol that need to be abated for tackling global warming increase. The main usage of HFCs is in room and mobile air-conditioning and refrigeration, while there are also significant applications for the industrial sectors related to and thermal insulating foams with minor uses in fire protection and as solvents. Xu et al. (2013) show that HFC emissions, if not constrained, could potentially contribute almost 20% to the total global warming by 2050. HFC use is expected to increase substantially with a transition away from Hydrochlorofluorocarbons (HCFCs) as HFCs are expected to replace HCFCs in most of the applications.

Though current per capita contribution of India to global warming is marginal at best, the role of India in responding to the global challenge of climate change cannot be overemphasized. Indian GDP is expected to grow significantly, leading to increases in primary energy consumption by over four times between 2010 and 2050 (Shukla and Chaturvedi, 2013).

Final energy grows from 18 EJ in 2010 to 79 EJ in 2050, and commensurate carbon emissions from 440 MTC to 2503 MTC (Chaturvedi and Shukla, 2013).

Earlier studies have highlighted that energy requirements for cooling buildings will grow at a pace higher than most of the other energy demands in the Indian buildings sector (Chaturvedi et al., 2013). Interestingly, the use of room air conditioners leads to three different categories of GHG emissions- one is indirect emissions from the burning of fossil- and bio-fuels to generate electricity to power the ACs, another is direct HCFC/HFC emissions as HCFCs/HFCs are used as refrigerant for cooling purposes, and the third is the "embodied" carbon emissions from the production, service, and recycle at the end of product life. Life-Cycle Climate Performance (LCCP) is the analytical technique to account for all three categories of heat-trapping emissions. Given the recent sales data for the past few years, air-conditioner demand for meeting room space cooling requirements in India is growing rapidly at a pace of 20-25% per annum (PwC, 2012). Expectations of rapidly increasing penetration of air-conditioners with increasing incomes in both the near-term and long-term is leading to increasing concerns around both direct and indirect greenhouse gas emissions from this sector. Apart from income effects, another key driver of cooling demand is increasing temperatures as the US experience has shown (Hojjati and Wade, 2012). It can be concluded with high certainty that global warming induced temperature shifts will only further spur the increase in demand for space cooling technologies in India.

After the invention of CFCs in 1928, fluorocarbons rapidly replaced toxic and flammable refrigerants until the efforts to protect the ozone layer began phasing out CFCs and HCFCs in the 1990s (Andersen et al., 2013). Developed countries with fast phase-out schedules choose HFC for many applications such as room and motor vehicle air conditioners, but are now shifting to lower-GWP alternatives such as natural refrigerants (hydrocarbons, ammonia, carbon dioxide), low GWP HFCs (HFC-152a, HFC-32) and very low-GWP synthetic fluorocarbons (hydrofluoroolefins - HFOs). Markets in India, as well as around the world, are transitioning away from ozone depleting HCFCs under arrangements of Montreal Protocol. However, HCFCs are being replaced by HFCs, mainly HFC-410a in the case of room air-conditioners, which have global warming potential magnitudes higher than that of carbon dioxide. HFC-410a has a IPCC AR5 $GWP_{100\ yr}$ of 1923significantly higher than the HCFC-22 (AR5 $GWP_{100\ yr}$ =1760) it replaces. Studies have highlighted the need to leapfrog from HCFCs directly to low global warming potential gases or natural refrigerants and have showcased efforts made by Indian and foreign companies in developing such alternatives (NRDC, CEEW, TERI and IGSD; 2013). However, there is incomplete understanding of costs and benefits of this transition towards low-GWP HFCs and natural refrigerants such as hydrocarbons, CO2, and ammonia,. Our study aims to contribute to this literature.

Given the discussions above, indepth research on HFC emissions scenarios from the Indian residential sector, and the implications of the transition away from HFCs, are clearly important research gaps. Our research aims to address these research gaps. We address the following research questions, all in the context of residential cooling sector - (i) given the impending transition of air-conditioning equipment from HCFCs to HFC-410a, what is the future long term emissions (direct HFC-410a and indirect carbon emissions) under reference scenario and a low growth scenario ; (ii) what are the energy and global warming implications of energy efficiency improvements while transitioning to alternative gases; (iii) how much of HFC410A emissions can be mitigated through best practices ; and (iv) what are the implications of a sustainable lifestyle for direct and indirect emissions?

We undertake our analysis within the integrated assessment modelling framework of Global Change Assessment Model (GCAM). The methodological framework is described in the next section on methodology, where we explain our detailed HFC emissions calculation module within the larger GCAM framework. This is followed by the results section that describes results from our scenario analysis. Finally, we discuss the policy implications from our research and present our key conclusions.

2. METHODOLOGY: SCENARIO ARCHITECTURE, MODELLING FRAMEWORK, AND ASSUMPTIONS

2.1 Scenario Architecture

For answering the research questions, we analyse a suite of HFC emission scenarios developed around assumptions related to socio-economic behaviour, technological factors, and drivers of HFC leakage. Detailed scenario names and descriptions are presented in Table 1. Our reference scenario is the Aspirational Lifestyle Scenario (AL sc), in which there is high economic growth leading to people buying more and more floorspace and driving cooling energy consumption up significantly. However, building energy efficiency and AC energy efficiency improvements are modest at best, and there is negligible effort to curb HFC-410a emissions from AC equipment usage. Note here that we follow the HCFC phase-out management plan (HPMP) in our reference AL scenario. Our second scenario, Low Economic Growth (LEG sc), explores the economic sensitivity of our reference scenario and analyses a world in which economic growth of India is much lower, which leads to lower floorspace expansion and cooling energy demand. Assumptions around technological factors and HFC emission drivers are same as the AL sc. We view this scenario as a pessimistic scenario for growth in Indian cooling energy demand, and hence present this as the lower range of future residential sector HFC emissions for India.

Our third and fourth scenarios test the energy and emission implications of transition towards two alternative refrigerants- R32 (HE32 sc) and R290 (HE290 sc). It has been argued that transition towards alternative refrigerants provides significant opportunities for improving energy efficiency gains through design and technology changes. We explore this theme by comparing these two scenarios with our reference AL sc. We assume higher increase in the energy efficiency of ACs in GCAM leading to lower electricity consumption and indirect emissions, while the HFC module estimates the savings in terms of carbon dioxide equivalent direct HFC emissions.

The HFC best practice scenario (HBP sc) explores the implications of best practices in managing direct HFC-410a emissions from AC equipment by reducing leakage during equipment operation as well as minimizing end of life emissions. All other socio-economic and technological factors remain same as in the case of the reference AL sc.

Finally, we explore the implications of a sustainable lifestyle scenario (SL sc) for 410A emissions. This scenario assumes same high economic growth as the case in the reference AL sc, but envisages sustainable socioeconomic behaviour in which people live in smaller homes (lower floorspace elasticity), adopt intensive building envelop efficiency measures and more efficient AC equipment, as well as undertake measures for minimizing direct HFC-410a emissions.

Together, these six scenarios provide us with a very good understanding of the some important questions and uncertainties related to HFC emission scenarios for India.

Table 1: Scenario Descriptions

Scenario Name	**Scenario definition**	**Scenario Characteristics**						
		Socio-economic behaviour			Technological factors		HFC emission drivers	
		Per capita income growth	Floor space elasticity	AC adoption rate (Endogenous)	Building envelop efficiency improvements	AC efficiency improvements	Leakage rate	End of life recovery
AL sc	Aspirational lifestyle sc-410A	High	High	High	Low	Low	High	Low
LEG sc	Low economic growth sc	Low	High	Low	Low	Low	High	Low
HE32 sc	High AC efficiency sc-R32	High	High	High	Low	High	High	Low
HE290 sc	High AC efficiency sc-R290	High	High	High	Low	High	High	Low
HBP sc	HFC best practice sc	High	High	High	Low	Low	Low	High
SL sc	Sustainable lifestyle sc	High	Low	High	High	High	-	-

2.2 Modelling framework

We undertake our analysis within the integrated assessment modelling framework of GCAM. GCAM integrates components on socio-economic human system that drives energy production and consumption, land-use system, and climate system within the same framework. The GCAM world is divided in 14 regions with India being a separate region. The partial equilibrium energy module within GCAM tracks production and consumption of fossil energy (conventional and unconventional coal, oil, and gas), nuclear energy, and renewable energy (solar, wind, geothermal, hydro). The share and penetration of any given energy technology is driven by its cost relative to other competing technologies. GCAM tracks emissions of carbon dioxide as well as other greenhouse and non-CO2 gases. GCAM operates in five year time step with the time horizon being 2095. However, for the purpose of this study, we limit our results and discussions to 2050, to make it more aligned with the HFC policy discussions happening in India which are mainly for this time horizon. Please refer Calvin et al. (2009); Wise et al. (2009); Thomson et al. (2011), Kyle and Kim (2011), Edmonds et al. (2012), Eom et al. (2012); Chaturvedi et al. (2013) for details about GCAM.

GCAM has three end use sectors- buildings, industry, and transportation. The building sector tracks energy service demand for urban residential, rural residential, and commercial buildings. The model tracks energy demand and consumption for five services- cooling, heating, cooking, lighting, and appliances. Building sector model is described in detail in Chaturvedi et al. (2014) and the current version has only minor updates compared to the version described in the paper.

We develop a separate module for tracking HFC emissions and soft-link it with GCAM (Figure 1). Based on total cooling energy demand (GCAM output) and unit energy consumption by an air-conditioner (AC) for any given year, we estimate the number of ACs in India from 2005 to 2050. The number of new versus old ACs is determined based on a vintage structure assuming the average lifetime of a typical AC being equal to 10 years. HFC emissions for any given year are calculated based on assumptions around charge rates, leakage rates, and end of life collection of AC units. We hence model, cooling energy demand under the top-down modelling framework of GCAM, and detail it with a more disaggregated bottom up assessment that gives us a more robust sense of HFC emissions as these emissions are closely linked to the actual number of ACs being employed in the residential sector.

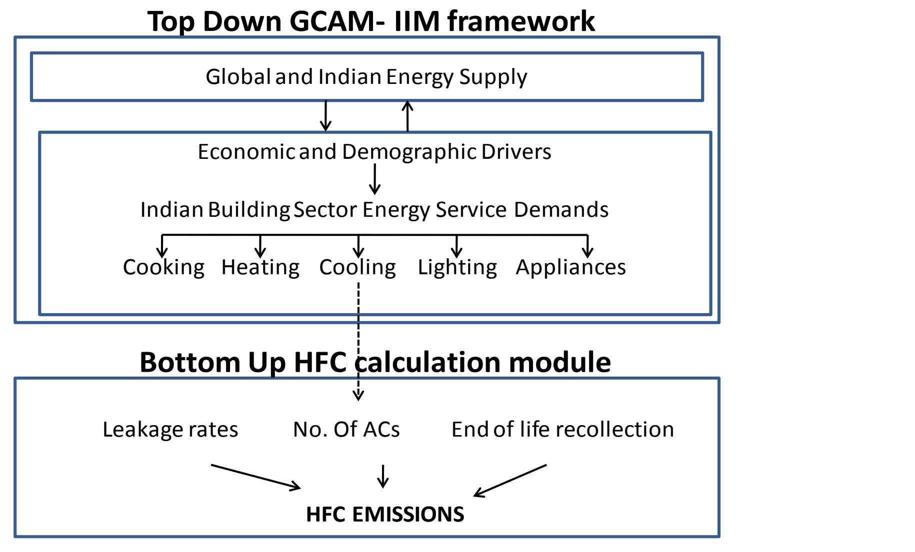

Figure 1: Methodological Framework

We calculate the number of AC units in India by dividing the total cooling energy consumption output of GCAM with the average energy consumed per unit AC for each future year. For targeting future HFC emissions from the sector, results from vintage-equipment-model are combined with projections from national HPMP[1] roadmap (Ozone Cell, 2013). Under HCFC phase-out schedule of Montreal Protocol for Article-5 Parties[2], India froze its HCFC consumption starting from January 1, 2013 and by 2014 consumption level is projected to reach average of 2009 and 2010 level (HPMP baseline target). From this date onwards, it is prohibited to add new capacities to manufacture products with HCFC although prohibition on import of HCFC based air-conditioners comes in place later from 1st July 2015 (Duraiswami, 2014). Detailed HPMP roadmap and projections derived from it for further years up to 2040 are detailed in Figure 2 and are applied to the equipment-model that gives the ODS[3] free equipment base. The emissions module works with simplistic assumptions that reductions in R-22 equipment base are proportional to the targets for reductions in HCFC consumption. R-22 is a stand-alone option for ODS equipment base. 89% of R-22 demand in 2009 for new equipment comes from air-conditioning sector of which more than 99% were small sized equipment (< 3 TR[4]) (Ozone Cell, 2013). Also, penetration of ODS-free equipment prior to commencement of HPMP schedule has been neglected in absence of market data for current penetration of R-22 substitutes. In any case, R-22 substitutes constitute a small proportion of overall stock at the moment and it will only marginally affect the modelled population of ODS-free equipment in near-term and will give same results in mid-term and long-term as industry aligns with HPMP targets for reduction in ozone depleting substances. Projections as given in Figure 1are applied for reduction in newly introduced R-22 equipment in the market. Five yearly reduction targets (PwC, 2012) are applied to the newly-introduced equipment in constant yearly step changes so that the equipment are no new R-22 based unit is sold in the market after 2030. This assumption is derived from the fact that there will be complete ban on manufacturing of R-22 room air-conditioners starting from 2025 (Phadke et al., 2013) but it is envisioned that there will still be R-22 units for five subsequent years and available R-22 in market (2.5 % baseline consumption) will be enough for servicing demand of old equipment for next ten years, up to 2040. Resulting ODS-free equipment from this framework of calculations constitute part of stock that is chosen for HFC emission calculations as detailed in the Appendix 1. We base our technical assumptions on Calm (1994), Myhre et al. (2013), Bitzer (2013), IPCC (2006),

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[1] HCFC phase-out management plan

[2] Article 5 Parties are developing countries with CFC consumption <0.3/ kg/ yr/ capita or if decided by Parties.

[3] Ozone depleting substance

[4] Tonne of Refrigeration, 1 TR = 3,517 W

Kataoka (2014), Rajadhyaksha (2014), Virmani (2014), and IPCC/TEAP (2006) as explained in Appendix.

Figure 2: National HCFC reduction targets as percentage of baseline level and projected declining sales of R-22 equipment for calculating HFC emissions

2.3 Data and Assumptions

Our scenario architecture is built around a set of assumptions on economic growth, floor space elasticity, building envelop efficiency, average AC equipment efficiency, leakage rate and end of life AC equipment recovery. Table 2 gives our assumptions for some of these variables.

Table 2: Scenario Assumptions

			2010-20	2020-30	2030-40	2040-50
Per capita GDP growth (% per annum)	High		6.9	6.5	6.3	5.9
	Low		5.4	5.0	4.8	4.4
		2010	2020	2030	2040	2050
Building envelop efficiency (Building U value in Watts/mt^2/Kelvin)	High	2.83	2.60	2.40	2.21	2.03
	Low	2.88	2.74	2.61	2.48	2.36
AC equipment efficiency (Energy Efficiency Ratio)	High	2.65	3.00	3.27	3.53	3.8
	Low	2.65	2.75	2.85	2.97	3.1

For the floorspace elasticity, we have assumed under the AL sc that consumers aspire to buy bigger homes and floor area and income is the only constraining factor, however under the SL sc consumers choose smaller floorspace and homes. Based on observed per capita GDP and per capita floorspace trends across different countries of the world (Chaturvedi et al., 2014) we have assumed that the maximum per capita floorspace under the high floorspace elasticity scenario is 45 m^2/capita in 2095, and is 32 m^2/capita in 2095 for the low floorspace elasticity scenario. Also cooling energy demand (or high/low AC adoption rate) is an endogenous variable to the model and is affected by assumptions around income growth and floorspace elasticity.

3. RESULTS FROM MODELLING ASSESSMENT

3.1 Model validation

The focus of this study is HFC emissions scenarios, which are critically dependent on our estimates of the number of ACs in the market. Ideally, we would have liked to calibrate our HFC emission estimates to the available data. HFC emissions for India have been indirectly estimated during inventory assessments. Comparing our estimates to estimates made during inventory assessments is hence of limited value for the purpose of our model validation.

The second best way to compare estimates of our model is to compare AC stock/sales data with that of actual sales data. This is the approach we choose for validating our model results. We first take stock data for year 2005 as calculated in Chaturvedi et al. (2014), add yearly sales data to it, and arrive at a 2010 stock number that we compare to our model results. Following table shows our detailed calculation for arriving at 2010 stock figures from market data.

Table 3: Estimating residential AC sales between 2005 and 2010

	Variable	2006	2007	2008	2009	2010		Source
A	Total room AC sales	1.5	1.85	2.2	2.75	3.44	Mn	PwC (2012)
B	Share of split AC in room AC sales	55	59	62	65	68	%	PwC (2012) gives 2009 and 2010 shares. Shares for other years are assumed
C = A*B	No. of split ACs	0.83	1.09	1.36	1.79	2.34	Mn	
D = A-C	No. of window ACs	0.68	0.76	0.84	0.96	1.10	Mn	
E	Share of residential ACs in split AC sales**	50	50	50	50	50	%	Based on Phadke (2013)
F	Share of residential ACs in window AC sales	80	80	80	80	80	%	Based on Phadke (2013)
G = C*E	Residential split AC sales	0.41	0.55	0.68	0.89	1.17		
H =D*F	Residential window AC sales	0.54	0.61	0.67	0.77	0.88	Mn	
I = G+H	Total residential AC sales	0.95	1.15	1.35	1.66	2.05	Mn	
	Total residential AC sales in 5 years					7.17	Mn	

** It should be noted here that as Phadke mentions that all room AC sales are not for residential establishments. Many small commercial enterprises also use room AC for meeting their cooling requirements. We hence use their estimates of this split to derive residential AC stock estimates from the total room AC sales.

Total AC stock in India in 2005 was 2.60 Mn ACs (Chaturvedi et al., 2014). Assuming that no ACs in 2005 have retired from the stock, and adding our estimates, total residential AC stock data in 2010 based on market data is estimated as 9.77 Mn. As per our model projections, total number of ACs in 2010 is 9.66 Mn, the number being very close to estimates based on survey and market sales data. This hence shows that model output for future AC estimates has been validated.

3.2 Assessing low and high range of direct and indirect emissions

Reference scenario or high growth scenario (AL sc) results

Whether direct and indirect GHG emissions from residential ACs will grow rapidly or not depends on a number of factors. Arguably the most important factor driving the demand for ACs is income. High income growth will result in higher demand for ACs compared to a comparatively lower income growth, even if cooling demands are critically dependent on other factors like ambient temperature and heat. Increasing temperatures will increase the latent demand, which can be realized only if economic and budget constraints of a consumer are relaxed.

Under the AL sc, which is also our Reference case, HFC 410A emissions grow at a much faster rate compared to indirect electricity emissions. Indirect carbon dioxide emissions increase by six times between 2020 and 2050, while the corresponding increase in HFC emissions is 24 times (Figure 3a). This implies that of the total global warming impact of residential GHG emissions from the residential AC sector, HFCs' contribution will be 24% in 2030 and 32% in 2050.

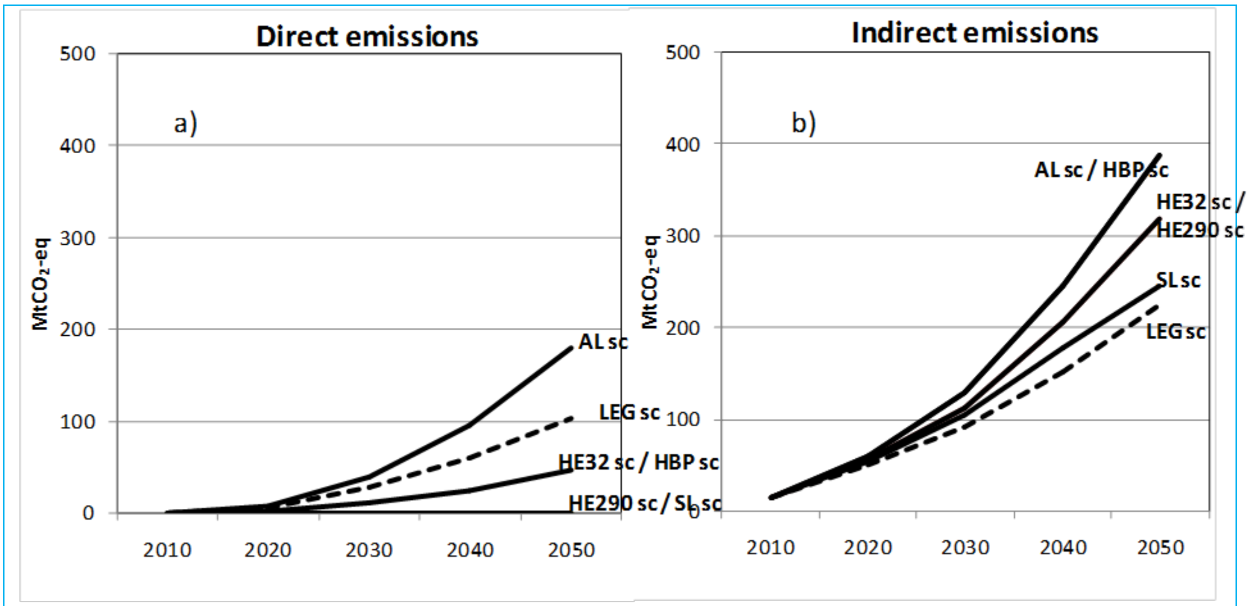

Figure 3: a) Direct emissions from residential AC sector, and b) Indirect emissions from residential AC sector

Carbon emissions grow with increased usage of electricity for running ACs, even though new ACs are more energy efficient. Highest growth in electricity consumption is observed between 2010 and 2020 because of the low base as well as increase in per capita income (Fig 4a). AC electricity consumption increases by four and a half times during this period of 10 years, next 20 years also witness a similar increase of four and a half times.

The growth in indirect emissions is lower compared to HFC emissions growth mainly because of two reasons. Most importantly on the supply side, the carbon intensity of electricity production declines substantially even under the AL sc with a move toward zero carbon sources (Fig 4b) as well as higher transformation efficiencies in the power sector. Between 2010 and 2050, a higher share of nuclear energy and renewable in India's electricity portfolio leads to a decline in carbon intensity of electricity by 30%. The second reason is the increase in efficiency of AC equipment. Average energy efficiency ratio (EER) of new stock of ACs increases to 3.1 in 2050 compared to stock average EER of 2.6 in 2005. It should be noted here that current 5 star rating as per Bureau of Energy Efficiency (BEE) related to an EER of 3.1. Our assumption of 3.1 EER in 2050 implies that there will be a distribution of new ACs sold in 2050. Some of these may have much higher EER than 3.1, and some will have lower EER. Our assumption represents average new stock EER and can be argued as conservative assumptions. We also explore a higher energy efficiency scenario in the next section.

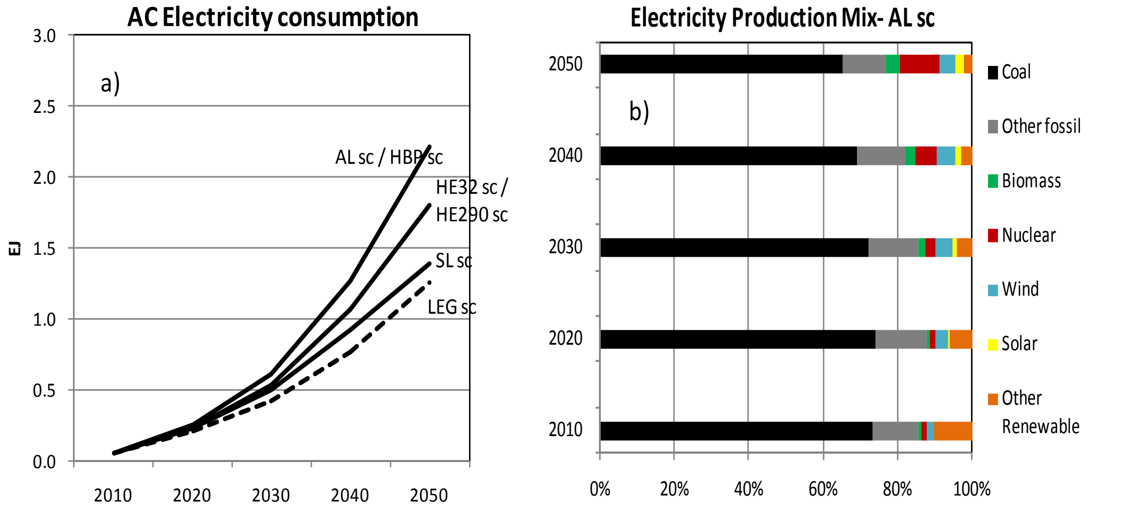

Figure 4: a) AC electricity consumption under various scenarios, and b) Electricity consumption under various scenarios

HFC emissions are based on assumptions about total AC stock and leakage rates. With no focused intervention on managing HFC leakage from AC equipments, there is no reason why leakage rates between now and the future will differ. Hence growth of HFC emissions largely track the growth in total AC equipment stock. Cooling energy requirement also reflect an increase in floor space demand. As people become wealthier, more and more floor space is sold (Figure 5a) and energy is consumed for cooling this floor space. Figure 5b shows the increase in residential AC sales under the high and low growth scenarios. Sales in the high growth scenario, which is also our reference scenario (AL sc), increase from over 2 Mn units in 2010 to 8.6 Mn units in 2020 and almost 60 Mn units in 2050.

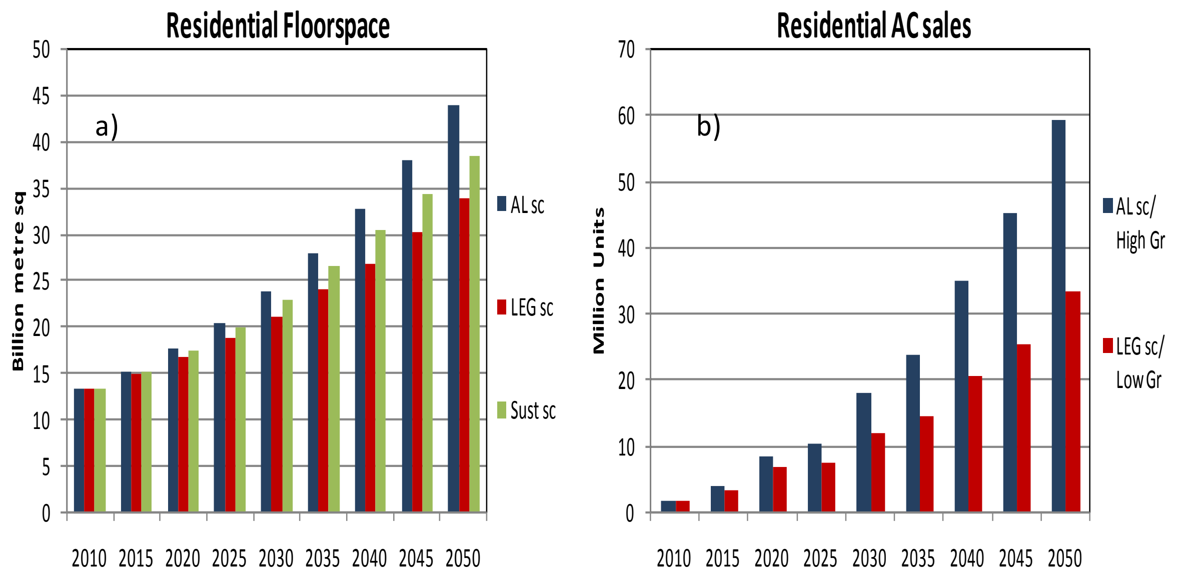

Figure 5: a) Residential floor-space under the different scenarios, and b) Residential AC sales under the high and low growth scenarios

Low growth scenario (LEG sc) results

Compared to a higher economic growth scenario, people demand lower floor space and lower energy for cooling this space under a low growth scenario. Total floor space demand under the LEG sc is lower by only 4% in 2020 but is lower by 23% in 2050 compared to the AL sc (Figure 5a). The biggest impact of lower economic growth is on the sales of AC units, which declines by 20% in 2020 and 32% in 2030 (compared to the AL sc), and by a huge 40-45% in the later years (Figure 5b). Electricity consumption hence also declines in similar magnitudes relative to the reference AL s (Figure 4a).

However even lower growth does not mean stagnation in AC sales or corresponding AC electricity consumption. AC sales under the LEG sc are also seven million in 2020, which increases to over 12 Mn by 2030 and 33 Mn in 2050. Thus both direct emissions and indirect emissions continue to grow at a significant pace (Figure 3). Carbon intensity of electricity is almost same under the AL sc and LEG sc as these scenarios don't assume a carbon price policy. In this case also HFC contribution in total GHG emissions from residential ACs is 10% in 2020 which increases to 32% in 2050. Thus, irrespective of the economic growth assumptions, the impact of HFC 410 A from residential ACs in global warming contribution of this sector is irrefutably high.

Sensitivity to leakage rate

As per IPCC/ TEAP report (2006), leakage rates in developing countries are very high compared to that in developed economies. Our assumption of leakage rate during AC operations is 10%, which as per the IPCC/TEAP report should be closer to reality. However as this is a critical assumption without any actual data available from the end use point, we also test the sensitivity of this assumption with a leakage rate assumption of 5%.

We find that direct emissions with a 5% leakage rate are closer to the LEG scenario emissions. We should note here that these two scenarios have been modelled independent of each other. Thus, even with a lower leakage rate we find a steady increase in HFC 410A emissions. As a share of total GHG emissions, HFC 410A still contribute to 16% of global warming potential (GWP) in 2030 and 23% of GWP in 2050.

Our sensitivity analysis shows that even with lower leakage rates, which as per our understanding underestimate the actual leakage rates, HFC emissions from the room air-conditioning sector do have a significant contribution in total GHG output from this sector.

3.3 Implications of transitioning to alternative gases

Two key alternative gases that have already penetrated the residential air conditioner market are the R32 and R290. R32 is being used by Daikin and has a mid-range global warming potential while R290 is being used by Godrej and has negligible global warming potential. Both the manufacturers, Daikin and Godrej, are claiming energy efficiency gains achieved through design modifications while moving towards alternative gases.

Though energy efficiency gains might not be directly because of switch to alternative gases, design choices while moving to alternative gases away from HFC 410A can certainly lead to significant energy efficiency gains and hence transition to alternatives presents a significant opportunity. We analyze two scenarios, one each for R32 and R290. This does not mean that we are proposing one or both of these gases for future transition. These gases are currently in the market and hence are we take these two as a representative of any alternative mid GWP gas and a low GWP gas that might be important for a HFC 410A free future. For our analysis, we assume same energy efficiency gains from the two gases, implying that the indirect emissions would be the same in both the cases.

HE32 sc is a mid GWP scenario, and confirms to EU- F gas regulation standards for use in the residential sector. Under this scenario, direct emissions in 2050 are reduced by 75% relative to the AL sc, and indirect emissions are reduced by 8-18% between 2020 and 2050 with higher energy efficiency. In terms of cumulative emissions between 2010 and 2050, direct emissions are reduced by 75% relative to the AL sc, and indirect emissions are reduced by 15%. Overall reduction in cumulative CO_2-eq emissions is 31%. We assume a higher EER of 3.8 achieved in 2050 with a transition towards alternative gases compared to an EER of 3.1 in 2050 in the AL sc.

HE290 sc is a low GWP scenario. As expected, direct emissions are negligible in this scenario, and almost 100% HFC emissions are eliminated. Energy efficiency related carbon reduction is same as in HE32 scenario. Overall reduction in cumulative CO_2-eq emissions is 38% between 2010 and 2050.

Interestingly, as direct emissions are reduced by 75% under the HE32 scenario compared to AL sc, HE290 sc leads to additional reduction of 25%. When compared to the AL sc, this implies a 100% reduction in direct emissions. As indirect emissions are two-thirds of the total GHG eq emissions from the residential AC sector, gains through energy efficiency are important and will play an important role in mitigating the overall GHG impact of this sector. We can conclude with a fair degree of certainty that with efficiency improvements during the transition away from HFC 410A as assumed in our study, moving to alternative gases can reduce the global warming impact of the sector by 31-38% during the period 2010-50.

3.4 How far can best practices for minimizing HFC emission from AC equipment take us?

Best practice scenario (HBP sc) assumes that in the scenario where ACs are still based on HFC 410A, best practices that can minimize leakage and can ensure end of life recovery of HFC 410A will be adopted. Leakage rate will hence be reduced to 1%, and end of life recovery will be increased to 90% with focused interventions. Hence this scenario is only focused at reducing direct emissions and not on energy efficiency co-benefits.

Interestingly, CO_2-eq emissions of HFC 410A under the HBP sc is same as the CO_2-eq HFC32 emissions under HE32 sc, which is mid global warming potential scenario. This means that if the high standards of best practices are adhered to as envisaged under this scenario, significant reductions in direct emissions can be achieved. However, this will still not lead to any reduction in indirect emissions due to same energy efficiency as in AL sc and hence is independent of any reductions in indirect emissions. In totality, cumulative GHG emissions between 2010 and 2050 from the residential AC sector can be reduced by 20%. We should note here that our assumptions related to best practice are stringent and achieving this would require significant management and operational challenges as leakages and recovery need to be managed not only at the level of factories, but at the level of servicing sector and each AC unit.

3.5 Sustainable lifestyle implications for energy and emissions

A sustainable lifestyle envisages multiple interventions at various levels. This scenario assumes that people will attain a wealthy lifestyle, but will adopt significant behavioural shifts compared to the Aspirational Lifestyle sc. Thus even with higher incomes, people will live in smaller homes with lower floor space (Figure 5a). Income induced adoption of ACs will be high, but AC technology will be more efficient. Moreover, this scenario envisages investment in building envelope efficiency measures towards more energy efficient building stock, which will have significant implication for cooling energy demand. This implies ACs with lower cooling capacities (e.g. 1 Ton AC compared to 1.5 Ton ACs) resulting in lower electricity consumption. Finally, the society transitions away from high GWP refrigerants towards natural refrigerants and so there is no role of best practices in terms of minimizing equipment level leakage and recovery.

Floorspace demand under the SL sc is reduced by 12% in 2050 relative to the AL sc (Figure 5a). With lower floor space, higher AC efficiency, and improved building efficiencies, electricity consumption is reduced by 10% in 2020, 18% in 2030 and 376% in 2050 relative to the AL sc (Figure 4a). Thus this scenario leads to an additional decline in electricity consumption in 2050 over the high energy efficiency scenarios (HE32/HE290 sc). As shown earlier, higher AC efficiency leads to 17% decline in electricity demand in 2050 relative to AL sc. Sustainable lifestyle leads to an additional decline of 19% points in 2050 with lower floorspace and higher building efficiency.

Multiple demand side measures described above lead to a decline in cumulative indirect emissions between 2010 and 2050 in the SL sc by 26% compared to the AL sc. As there are no HFC 410A emissions in this scenario, total global warming impact relative to the AL sc is reduced by 46%. In our scenario framing, the sustainable scenario has been defined only for the end use building sector. This is coupled with efficiency enhancing and low carbon policies on the supply side can be very beneficial for reducing primary energy demand in India.

4. DISCUSSIONS

4.1 Energy efficiency gains and co-benefits

Energy efficiency is often argued as a low hanging fruit. However energy efficiency measures have not been adopted in the Indian building sector the way they have been in the industrial or transportation sector. The reason is clearly 'split incentives'. In any non-building sector, energy efficiency gains directly accrue to the investor. However in the case of building sector, any intervention at the level of buildings implies that the project developer will invest while the gains will be accrued by homeowners or renters. If additional costs are passed on the prospective buyers, higher cost of energy efficient buildings makes these relatively unattractive to the buyer who has the option of buying lower cost homes. In the absence of any mechanism to take care of the issue of split incentives, efficiency improvements in the end use technologies remain the only resource for reducing building energy demand.

Given that cooling energy demand is bound to take a significant share in residential electricity consumption, efficiency gains in ACs should be viewed as an important resource. Moving towards high energy efficiency requires design changes, and transition towards alternative gases also requires design changes. The process of transitioning to alternative refrigerants hence provides a valuable opportunity to move towards higher energy efficiency designs to simultaneously reap the benefit of both lower direct emissions and lower electricity consumption.

Co-benefits from climate-focused interventions are emerging as a strong narrative that can provide a stronger rationale for investment choices in developing economies. Energy efficiency is a crucial co-benefit of the transition towards alternative refrigerants. Energy efficiency gains should be included in any analysis of the value in moving away from HFC 410A for the room air conditioner sector.

4.2 Cost of transition and funding mechanisms

Transitioning away from HFC 410A to low GWP or natural alternatives will entail costs. Higher cost can be due to design changes required for the alternative gases, training of human resource, patent issues and import of gases, as well as measures required for ensuring safety features of ACs running on alternative gases. Currently, there are no estimates in the available literature of industry level transition to alternative refrigerants. Irrespective of the estimates, the understanding is that this cost is not going to be small, even if it is not very high. The room AC industry is currently not ready to bear this cost on its own, and hence only two AC manufacturers have made a move towards alternative refrigerants.

Funding support for this transition can potentially come from alternative funding mechanisms. Internationally there is a debate going on this issue, with funding under Montreal Protocol as well as Kyoto Protocol being discussed and debated (Ghosh, 2013). Proponents of funding through Montreal Protocol arrangements argue that this mechanism has been successful in the past in transitioning away from CFC’s and HCFCs and hence it can deliver again. Proponents of Kyoto Protocol argue that HFCs are greenhouse gases and hence these fall under Kyoto's jurisdiction. These proponents claim that any move to bring the transition and funding under Montreal Protocol can potentially undermine the Kyoto architecture and set a negative precedent. Though arguments from both sides have pros and cons, what is important is that both the sides resolve this issue expeditiously in a time bound manner to avoid getting the world fixed in high GWP gases. A clearer sense of the costs of transition and funding mechanism will definitely propel the world towards a establishing an internationally agreed framework to expedite transition towards a low-GWP air conditioning sector.

4.3 A note on commercial sector cooling

Our paper has focused only on the residential AC sector. However as highlighted in the earlier sections, some room ACs are also used in the small commercial segment. However larger commercial establishments have different air-conditioning technologies as compared to small commercial or residential cooling technologies. Though we expect highest growth in floorspace in the residential sector, commercial space will also grow significantly. More importantly, the energy consumption density per unit floor space is much higher for large commercial establishments than room sized units. The insights from our residential sector focused analysis in our understanding would also be true for small sized cooling in commercial sector given that both electricity intensity as well as HFC intensity for this sector will exhibit similar relationship as in the case of room AC sector.

5. CONCLUSIONS AND POLICY IMPLICATIONS

Our current understanding of long-term HFC emissions from India is very limited. There are critical uncertainties like rate of economic growth, floor space expansion, improvements in building efficiency that can reduce cooling demands, rate of adoption of AC in vehicles, HFC emission leakage during lifetime, and end of life recovery and leakage all of which can have significant implications for the magnitude of India's long term HFC emissions.

Our study, set within the framework of integrated assessment modelling, contributes to the HFC scenario literature through focusing on the residential air-conditioning sector. We analyse a suite of HFC and alternative gas scenarios for understanding the implications for GHG emissions from this sector. We also test the sensitivity of HFC emissions from this sector to economic growth assumptions. We assume that HCFC phase out will happen as per the Montreal Protocol commitments and HFC410A will replace HCFC22 under the business as usual scenario.

Our first key finding is that if unabated, HFC410A emissions in 2050 will contribute to 32% of the total global warming impact from the residential AC sector in India, irrespective of future economic growth trajectory. However total emissions, direct and indirect, will be higher in the high growth trajectory by 50% compared to the low growth trajectory.

A move towards more efficient alternative gases will significantly reduce the cumulative direct and indirect emissions between 2010 and 2050. The associated reduction on the global warming footprint of this sector will be 31-38% during the period 2010-50, due to gains both from energy efficiency as well as low GWP alternatives. We should highlight here that global warming impact due to indirect emissions is due to the high fossil dependence of the electricity sector in India. Decarbonisation by moving towards low carbon fuels will lead to further decline in the global warming impact of this sector.

We show that if high standards of best practices are adopted for minimizing leakages during operation and end of life equipment life, then direct emissions can be reduced significantly, but as indirect emissions still contribute to a high share, overall cumulative GHG reduction benefit due to best practices will be fairly limited up to 20%. A sustainable lifestyle where people adopt lower floorspaces, and invest in overall building envelop efficiency along with transitioning to alternative gases is successful in reducing cumulative emissions by 46% compared to the Reference scenario.

Our study has some key policy insights. As we show that HFC 410A emissions have a significant contribution in GHG emissions from the residential AC sector, there undoubtedly needs to be a move away from this gas towards alternative gases. Additionally we also show that energy efficiency improvements achieved during this transition will have a significant effect on reducing the indirect emissions from this growing sector. The energy efficiency potential in both the end use technologies and building envelope efficiency needs to be harnessed. As building efficiency investments face the challenge of split incentives while the end use technologies directly provide financial savings to the investor, it is easier for market mechanisms to propel the latter while appropriate support and incentive structure is needed from the government for pushing the former.

Information on AC coolant recharge frequency and recovery rate of scrapped AC units is required for better estimation of direct emissions, and this is a near term action required. The government, by directing manufacturers and service providers to collect and provide this information, will be better able to understand the magnitude of HFC emissions in India. Additionally, creating sector wise guidelines for reporting of HFC emissions will be an important step.

Another important information challenge is the issue of cost and efficiency of alternative gases in the market. Though two alternatives, R-32 and R-290, are available, there are some more under research. Cost and efficiency of these alternatives will be revealed only with time. The government can either wait for getting more information on a larger suite of potential alternatives, or can facilitate transition towards the existing alternatives. Waiting also has a significant cost as the industry would have already made the transition towards HFC410A away from HCFC-22. The opportunity of leapfrogging from HCFC-22 to low GWP alternatives, if missed, will lead to fixities that will be costly to come out of.

Though cost and efficiencies of existing alternatives are provided by manufacturers, government need to undertake an independent technical assessment that can provide unbiased and reliable information to the market for making optimal choices suitable for individual manufacturers.

Our analysis is a first step towards a more comprehensive cost based assessment for informing strategies for a lower GHG impact of HFC consumption sectors. Along with carbon dioxide focused strategies, it is important to analyse and understand complementary strategies focused on non-CO2 GHGs for decreasing emissions from the country. Analysing non-CO2 gases from various dimensions is an important research theme that should be analysed in India and is a future research direction in which climate policy research in India should move.

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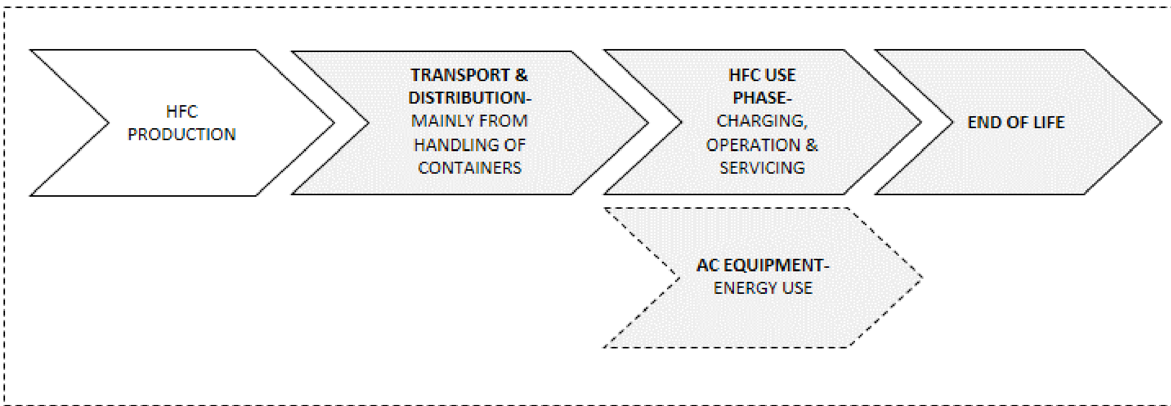
APPENDIX - DIRECT EMISSIONS: EMISSION FACTORS APPROACH

This Appendix explains the technical assumptions and methodology of the HFC module in detail. The emissions from hydrofluorocarbon use in air-conditioners are calculated by emission factors approach where-in generalised assumptions for leakage rates, at different stages for gas-use (Figure A1) are used. In absence of national guidelines that exist for calculation of sectorial emissions from HFC-use, IPCC recommendations on emission factors for developing countries (IPCC, 2006) have largely been adapted for this study and are summarised in Table A3, for different scenarios discussed in the report. Global Warming Potentials (GWP) for different gases (Myhre et al, 2013) are also given in the Table A2 and for only HFC blend: R-410a, GWP value is calculated assuming equal share of R-32 [50%] and R-125 [50%] in the blend (Bitzer, 2013) (IPCC 2006). The GWP value for R-125 is 3170 g-CO2/g (Myhre et al 2013).



PRODUCTION	TRANSPORT & DISTRIBUTION	USE	END OF LIFE
Leakages at production site	Leakages from handling gas containers	Leakages at charging site	Release at the end of equipment life
Emissions from energy use for manufacturing	Energy use for transportation	Leakages during equipment operation	Energy use for gas recovery
	Atmospheric dispersion	Servicing leakages	Atmospheric dispersion
		Emissions from equipment energy use	
		Atmospheric dispersion	

Figure A1. Emissions during various stages of gas-use that are considered for this study

Table A1. Properties of R22 and its substitutes studied in this report								
GAS	COMPOSITION	ODP [gR11/g]	GWP^{100}_{YEARS} [gCO_2/g]	LIFETIME [YEAR]	SAFETY GROUP	BOILING TEMPERATURE [^{O}C]	TEMPERATURE GLIDE [^{O}C]	CRITICAL TEMPERATURE [^{O}C]
R-22	$CHClF_2$	0.055	1760	11.9	A1	-41	0	96
H-410a	R-32 (50%), R-125 (50%)	0	1924		A1	-51	< 0.2	72
R-32	CH_2F_2	0	677	5.2	A2	-52	0	78
R-290	C_3H_8	0	3	0.041	A3	-52	0	97

	LOWER TOXICITY	HIGHER TOXICITY	
HIGHER FLAMMABILITY	**A3**	**B3**	LFL ≤ 0.10 kg/m^3 or heat of combustion ≥ 19000 kJ/kg
LOWER FLAMMABILITY	**A2**	**B2**	LFL > 0.10 kg/m^3 or heat of combustion < 19000 kJ/kg
NO FLAME PROPAGATION	**A1**	**B1**	no LFL based on modified ASTM E681-85 test
	No identified toxicity at concentration ≤ 400 ppm	Evidence of toxicity below 400 ppm	

Figure A2. Safety groups for refrigerant gases, adopted from ASHRAE journal (J. Calm, 1994)

Table A2. Assumptions for Reference and Mitigation/ best-practices scenario on HFC emissions

SCENARIO-SPECIFIC ASSUMPTIONS ON EMISSION FACTORS	DISTRIBUTION PHASE	HFC- USE PHASE				END-OF-LIFE PHASE	
	FROM HANDLING CONTAINERS [% OF MARKET]	OPERATIONAL LEAKAGES [% OF INITIAL CHARGE / YEAR]	LEAKAGES FROM INITIAL CHARGING [% OF INITIAL CHARGE]	REMAINING CHARGE FOR SERVICING [% OF INITIAL CHARGE]	LEAKAGES FROM SERVICING RECHARGE [% OF SERVICING RECHARGE]	REMAINING CHARGE AT END-OF-LIFE [% OF INITIAL CHARGE]	RECOVERY EFFICIENCY [% OF REMAINING CHARGE]
REFERENCE/ BUSINESS-AS-USUAL SCENARIO	10 %	10 %	1 %	60 %	2 %	80 %	0 [5]
INTERMEDIATE LEAKAGE SCENARIO	10 %	5%	1 %	65 %	2 %	85 %	0
MITIGATION/ BEST-PRACTICES SCENARIO	2 %	1 %	0.2 %	NA	0.4 %	90 %	80 %

[5] No end-of-life recovery is being made

The key information that is required for emissions calculations is, charge rates for units based on different refrigerant gases. These rates depend on the fluids' characteristics and their thermo-physical properties in addition to any limits that safety requirements might impose on their use owing to their toxicity and/or flammability. As can be seen in Table A1, HFC-32 falls under safety group- A2 which means a lower flammability but flame propagation is still observed at higher concentrations (Figure A2), compared to R-290, for instance. Equation 1 was developed as a result of various tests and numerical analyses (Kataoka, 2014), and is used extensively around the world to determine the safe charge limits for gases with high or limited flammability. It has also been adopted for numerous standard like IEC 60335-2-40, ISO 5149 and EN 378.

$$m_{max} = 2.5 * LFL^{5/4} * h_0 * \sqrt{A}$$

Equation 1

m_{max}: Maximum allowable charge [kg]
LFL: Lower Flammability Limit [kg/ m^3]
h_0: Installation height[m]
A: Floor area [m^2]

The R-290 units were introduced in India by Godrej and typical charge rates for these units are found to be 0.36 kg for a 4.8 kW unit [Rajadhyaksh, 2014]. This charge rate is verified by using Equation 1 for calculation of safe charge limits of R-290.For'lower flammability limit' value: LFL (R-290) = 0.038 kg /m^3 [Kataoka 2014], and typical values (Rajadhyaksha, 2014) of installation height: h_0 =2.2 m and floor area: A = 15 m^2; the resulting values of safe charge limit- m_{max} is found to be approximately 0.36 kg. This analysis provides the input for charge rate for R-290 in emissions calculations, which is 74.5 g/ kW. Also, looking at the specification sheets of existing equipment (Rajadhyaksha, 2014), typical charge for R-22 is found to be 0.75 kg for a 5.2 kW unit which means a charge rate of 144 g/ kW. For cooling performance of refrigerants equivalent to R-22, it is found that nominal charge rate for R-410a and R-32 is found to be 97% and 70% to that of R-22 (Virmani, 2014). This provides the charge rates for both HFC substitutes- R-410a and R-32 and are found to be 140 g/kW and 101 g/kW respectively. Further owing to the flammability of R-32, the safe charge limit for R-32 with LFL = 0.306 kg / m^3 (Kataoka,2014) and using the same set of assumptions for room size (as in the case of R-290), is found to be 97 g/ kW. This is in close approximation to the actual value used as model input (=101 g/kW). Although calculation of emissions at different stages presented below apply for reference scenario (HFC-410a), methodology for different scenarios is essentially the same and slight changes that might occur, are explained at each stage.

HFC-emissions are calculated under two key scenarios- Reference and Mitigation/ Best-practices scenario. In *reference scenario,* there is no government regulation and action on limiting gas releases during operation and servicing, and subsequently no action on removal at the end of equipment life. Leakage rates at different stages of HFC use and recovery rates used for this case are indicative of this business-as-usual scenario. In *mitigation/ best-practices scenario,* a concrete action and regulation is in place for limiting leakages of gases and removal at the end of life. Various assumptions on different factors used for emission calculations have been tabulated in Table A2.

For small sized pre-packaged air-conditioning units, the leakages while charging the new units take place at the factory. These are one- time emissions that occur only once during unit's life-time. They are lower compared to charging leakages for large-sized ducted equipment that require field erection and subsequently onsite charging. *Equation 2* depicts calculation for factory emissions in reference case and are calculated on the basis of initial charge in new equipment that are added to the pool of total equipment in a year.

$$\boldsymbol{E^{factory} = k_{charging} * N_0 * r_{charge} * Q_c}$$

Equation 2

$E^{factory}$: Annual emissions at the factory owing to the initial charging of air-conditioners [t R-410a]
$k_{charging}$: Leakage rate at the charging site as percentage of initial charge [% of Initial charge]
N_0: Number of newly introduced units in a year [units/ year]
r_{charge}: Charge rate for a unit based on particular refrigerant [kg/ kW]
Q_c: Cooling capacity of an average room air-conditioner unit [kW] = 5.07 kW

The initial charge in new equipment along with the factory leakages give the yearly market demand of refrigerant excluding the servicing demand. This segment of refrigerant market is calculated as in Equation 3.

$$D^{newunits} = (1 + k_{charging}) * N_0 * r_{charge} * Q_c$$

Equation 3

$D^{newunits}$ = Yearly refrigerant demand for new units [t R-410a]
The operational leakages are further calculated for the stock of equipment in a year which includes both new and vintage equipment. These emissions occur for each year of equipment's life–time and are thus labelled as life-time emissions. They are calculated applying the annual leakage rates as percentage of initial charge on total stock of equipment in a year. There are three different leakage rates that have been used in this study, 10% for reference scenario, 5% for intermediate leakage scenario and 1% for mitigation or best practices scenario. These operation leakage rates have further repercussions for the servicing- emissions and demand.

$$\boldsymbol{E^{operational} = k_{operational} * \sum_{0}^{9} N_i * r_{charge} * Q_c}$$

Equation 4

$E^{operational}$: Annual operational emissions from air-conditioners [t R-410a]
$k_{operational}$: Leakage ratesduring life-time of equipment [% of Initial charge/ year]
$\sum_0^9 N_i$: Total stock of equipment in a year (new and up to 9 years- old) [Units/ year]

For reference scenario (HFC-410a), 10% operational leakages demand recharging twice in unit's lifetime. Another implicit assumption for this being, the room air-conditioner undergoes recharging whenever the refrigerant charge declines to 60% of initial charge. Based on this set of assumption for reference scenario, It is 4 years- and 8 years- old equipment that require recharging in a year and adds to the servicing- emissions and demand in that year. In case of intermediate leakage scenario (5% leakage rate), servicing recharge only occurs once, when equipment is 7 years- old and remaining charge is around 65 %. With an exception, there are no recharges in mitigation /best- practices scenario as leakage rates are very low and equipment still has 90% of charge left at its end of life. Actual calculations for reference scenario- servicing emissions are given in Equation 5. The leakage rate for servicing recharges are assumed to be double than for initial charging to compensate for additional gas that is being released into atmosphere while repairing the leakages. While servicing, refrigerants are released during procedures for leak detection and at times, refrigerants are also used to rinse out any moisture, contaminants or air in the refrigerant loop (IPCC/TEAP, 2006).

$$\boldsymbol{E^{servicing}} = [\boldsymbol{k_{recharging}} + \boldsymbol{c_{servicing}} * (\mathbf{1} - \boldsymbol{e_{servicing}})] * \left[\left(\sum_{\mathbf{charge<60\%}} \boldsymbol{N_j}\right) * \boldsymbol{r_{charge}} * \boldsymbol{Q_c}\right]$$

Equation 5

$E^{servicing}$: Annual emissions at servicing site [t R-410a]
$k_{recharging}$: Leakage rates for servicing recharges [% of servicing recharge]
$c_{servicing}$: Remaining charge while servicing [% of initial charge]
$e_{servicing}$: Servicing sector recovery efficiency [% of remaining charge for servicing]
$\left(\sum_{\mathbf{charge<60\%}} \boldsymbol{N_j}\right)$: Number of old units in a year with charge remaining less than 60% [Units/ year]

Factors in second column of Table A2 are used for calculating emissions from handling containers which occur while transferring gases from bulk containers to small sized containers between 0.5 kg to 1 tonne of small containers and from gas- heels left in these various containers (IPCC, 2006). It is assumed that air-conditioner industry utilises bulk containers (for initial charging), so there are very little or no emissions in this case from handling containers whereas most of the emissions from handling containers come from servicing sector where these gases are further being distributed in small containers for servicing recharges. The emission calculations for this category are given in Equation 5.

$$\boldsymbol{E^{container}} = \frac{\boldsymbol{k_{container}} * [(\mathbf{1} + \boldsymbol{k_{recharging}}) * \left(\sum_{\mathbf{charge<60\%}} \boldsymbol{N_j}\right) * \boldsymbol{r_{charge}} * \boldsymbol{Q_c}]}{(\mathbf{1} - \boldsymbol{k_{container}})}$$

Equation 6

$\boldsymbol{E^{container}}$: Annual emissions from handling containers [t R-410a]

$\boldsymbol{k_{container}}$: Leakage rates for container handling [% of Market demand]

The yearly demand from servicing of equipment comes from recharging of equipment, subsequent emissions from recharging and the container emissions which are significant for servicing sector due to transfer of gases from bulk to small sized containers. Total refrigerant demand for this segment of market is calculated as in Equation 7.

$$D^{servicing} = \frac{[(1 + k_{recharging}) * (\sum_{\mathbf{charge<60\%}} \boldsymbol{N_j}) * r_{charge} * Q_c]}{(1 - k_{container})}$$

Equation 7

$D^{servicing}$ = Yearly refrigerant demand from servicing sector [t R-410a]

In reference scenario, there is no recovery at the end of equipment's life and all the remaining charge (60% in reference scenario) is being released into the atmosphere. This is the case with no regulation on limiting HFC emissions. In mitigation scenario, recovery efficiency is assumed to be 80 % as there are some technical limits on possible recovery of refrigerant and some of it is left in equipment as gas heels. Although 80% of remaining charge (90% in mitigation scenario) in equipment is recovered at end of life, the fate of recovered gas is not very clear and is not accounted in emission calculations. Equation 8 represents the end of life emissions in a year that result from the retired equipment.

$$E^{endoflife} = c_{endoflife} * (1 - e_{endoflife}) * N_{10} * r_{charge} * Q_c$$

Equation 8

$E^{endoflife}$ = Annual end-of-life emissions [t R-410a]
N_{10} = Number of retired units in a year [Units/ year]
$c_{endoflife}$ = charge remaining in a unit at its end of life [% of initial charge]
$e_{endoflife}$ = end-of-life recovery efficiency [% of remaining charge]

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