Climatic Change (2017) 143:503–517
DOI 10.1007/s10584-017-2002-4

Long-term carbon dioxide and hydrofluorocarbon emissions from commercial space cooling and refrigeration in India: a detailed analysis within an integrated assessment modelling framework

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Received: 21 October 2016 / Accepted: 25 May 2017 / Published online: 9 June 2017

Abstract Quantification of greenhouse gas emissions is a critical research gap for space cooling and refrigeration applications in Indian commercial buildings. This is especially relevant as these services are expected to grow rapidly in future driven by economic growth and urbanisation. This paper focuses on these two applications which are highly energy and emission intensive, and quantifies their carbon dioxide (CO_2) and hydrofluorocarbon (HFC) emissions through soft-linking a top-down model with a bottom-up approach. An integrated assessment modelling framework Global Change Assessment Model (GCAM)-IIM is used for modelling energy-related emissions under a business-as-usual scenario. In addition to CO_2 emissions occurring from electricity use, cooling and refrigeration in commercial buildings emit another set of highly potent greenhouse gases, emanating from application of HFCs as coolant. HFCs substitute their ozone-depleting precursors in these applications. Countries across the world have agreed to phase down HFCs under the Montreal Protocol. Before we can analyse cost-effective options to bring down these emissions, it is important to quantify and assess the amount of emissions that could be avoided in the future. Our research sets up a baseline for carbon dioxide and HFC emissions from India for the commercial air-conditioning and refrigeration sectors and finds the potential HFC emission mitigation due to the Kigali Amendment. A detailed bottom-up modelling of these emissions is undertaken and it is found that, if unabated, the HFC emissions from commercial sector will surge from mere 1.8 million tonne (Mt) CO_2e in 2015 to 211 Mt CO_2e in 2050, whereas energy-related CO_2 emissions from commercial air-conditioning and refrigeration will rise from 37 to 297 Mt CO_2e

Electronic supplementary material The online version of this article (doi:10.1007/s10584-017-2002-4) contains supplementary material, which is available to authorized users.

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in the same period. We also highlight the role of management practices and regulation for curbing HFC emissions which is especially relevant for the commercial building sector.

Keywords Refrigeration and air conditioning · Commercial buildings · GHG emissions · Montreal Protocol

1 Introduction

Increasing evidence and confidence on the impacts of global warming has compelled policy makers around the world to act for mitigating climate change (IPCC 2014). There is significant research on mitigating carbon dioxide (CO_2) emissions (IPCC 2014), CO_2 being the largest contributor to global warming. Other greenhouse gases (GHGs) are also important, but there is a limited understanding of potential emissions of the non-CO_2 GHGs and strategies and cost for mitigating these, particularly in developing nations. Hydrofluorocarbons (HFCs), one of the six classes of non-CO_2 gases recognised under the second compliance period of the Kyoto Protocol, are chemicals with global warming potential (GWP) ranging from few hundred to several thousand times that of CO_2. HFCs are used as coolants across the world in stationary and mobile refrigeration and air conditioning (RAC) appliances and equipment, more commonly in developed world. Developing countries have recently started transitioning away from ozone-depleting hydrochlorofluorocarbons (HCFCs) towards HFCs. HFC emissions include both fugitive emissions during operational life of the equipment and inadvertent release of these gases into atmosphere during servicing or at the end of equipment life. Velders et al. (2015) suggests that global HFC emissions could reach as high as 5300 million tonne (Mt) CO_2e[1] by 2050, equivalent to 6–9% of projected global CO_2 emissions under business-as-usual (BAU) scenario. Along with CO_2 mitigation, it is important to phase down HFC consumption for mitigating climate change and global warming.

Both CO_2 and HFC emissions in India can be expected to grow at a rapid pace with increasing incomes and population. There are studies focussing on Indian carbon dioxide emissions, but clearly a lack of research on India's potential HFC emissions. Chaturvedi and Sharma (2016) show that the share of HFC emissions in total direct and indirect emissions from the Indian residential air-conditioning sector could be 33% by 2050. However, this study focuses only on the residential air-conditioning application. Another key sector in India's growth story is the commercial building sector, yet the potential growth of CO_2 and HFC emissions from this sector is poorly understood. At the time of writing and to the best of our knowledge, there are no detailed estimates available for installed capacities of various types of refrigeration/air-conditioning equipment in commercial buildings in India, as well as present and future trajectory of carbon dioxide emissions as a result of rapid urbanisation and resulting growth in commercial floorspace. Currently, the urbanisation rate in India falls short of global average,[2] and it is expected that by 2050, 50% of India's population will be urbanised (Census 2011; UN DESA 2014). This will result in tremendous growth in commercial floorspace and concomitant penetration of space cooling in commercial buildings. Also, a rapid increase in demand for refrigerated products and frozen goods is speculated, which will result in

[1] The 100-year GWP values are used in Velder et al. (2015) as per WMO (2014)

[2] Up to the last census period, urbanisation in India was recorded at 31.2%, whereas the global urbanisation crossed 50% mark in 2008.

development of supply chain for refrigerated goods which is not well developed in the country yet. Lack of data on the current profile of floorspace in this sector and lack of understanding of how different types of commercial buildings will grow in the future is a research gap that needs to be addressed for understanding the role of commercial building sector in India's GHG mitigation strategy.

Commercial buildings are fourth largest consumer of electricity in India following industry, agriculture and residential building sectors. Commercial buildings consumed roughly 9% of total electricity (70 TWh) in 2012, and this consumption has grown at an average growth rate of approximately 12% since 2006 (MoSPI 2013). Most commercial buildings in India consume energy in excess of 200 kWh/m^2/year (UNDP and GEF 2011), with air conditioning and refrigeration consuming highest amount of electricity, followed by lighting. In the commercial sector, out of the total electricity consumption, heating, ventilation and air-conditioning (HVAC) contribute to a major share at 55% (GoI 2014). Carbon intensity of electricity in India is very high due to heavy dependence on coal and stands at nearly 791 gCO_2/kWh compared to a global average of 522 gCO_2/kWh (IEA 2015). Air conditioning and refrigeration therefore have a huge carbon footprint due to electricity consumption that needs to be understood better.

In addition, commercial sector is transitioning from ODS to HFCs with very high GWP ranging from 124 to 14,800 (IPCC 2007). Table A2 in Appendix 2 gives an overview of different coolant options used in different sectors and their GWPs. Analysis presented in this study focusses on commercial RAC sector where large quantities of such gases are banked in small to very large sized RAC equipment. Although commercial refrigeration has already transitioned to HFC-134a in India, almost all commercial air-conditioning equipment except chillers[3] sold today utilises HCFC-22 (Ozone Cell 2013) and will need to transition to non-ODS alternatives under international commitments at Montreal Protocol to safeguard ozone layer. Leaders across the world have agreed to an amendment to the Montreal Protocol to transition away from high GWP HFCs. Our estimates intend to serve as a baseline for any future estimation of avoided HFC emissions from two important sectors in India due to the amendment. We also estimate the emission mitigation that could be achieved in these sectors due to the amendment. It is important to know how much HFC emissions could be avoided in key sectors and applications in India due to the impending transition.

To guide policy interventions and mitigate its potential GHG impact, it is critical to understand the potential trajectory of energy use and emissions from the commercial building sector in India. In this context, our research aims at answering the following research questions: (i) how would commercial floorspace and resultant electricity demand for cooling and refrigeration grow in India's commercial building sector?, (ii) how would CO_2 and HFC emissions from the Indian commercial air-conditioning and refrigeration sector grow in the BAU scenario up to 2050? and (iii) what would be relative contributions of HFC emissions compared to CO_2 emissions from this sector under the BAU scenario up to 2050? In our definition of BAU, the commercial cooling and refrigeration sectors evolve in India as these have evolved in developed countries, and high GWP HFCs are used as refrigerants in this world. This study quantifies CO_2 and HFC emissions from these two energy- and emission-intensive applications in commercial buildings for the period of 2010–2050. The detailed information on evolution of commercial RAC stock as modelled in this study is very useful for policymakers for undertaking domestic policy measures on energy efficiency and limiting/recovering HFC gases during their use in commercial equipment. This information is also useful for estimating mitigation due to the recently agreed amendment to the Montreal Protocol. We undertake our analysis

[3] Majority of chillers sold in the market utilise HFC-134a, HFC-410a and HFC-407c with exception of low-pressure HVAC systems sold by one manufacturer which use HCFC-123

under the integrated assessment modelling framework of Global Change Assessment Model (GCAM). Following sections present our methodology, data and assumptions, results and conclusions.

2 Methodology

2.1 Modelling framework

The modelling framework for estimating emissions is a combination of top-down modelling for energy service demand and associated CO_2 emissions in commercial buildings along with bottom-up calculation of HFC emissions using emission factor approach. An equipment vintage model has been used to predict time series of ODS and non-ODS equipment sales through calibration with India's HCFC Phase-out Management Plan (HPMP) data (UNEP 2012; Ozone Cell 2013). This framework is presented in Fig. 1 and various steps involved in estimating emissions are discussed throughout the methodology section and relevant appendices of the supplementary material.

Service demand for commercial energy services is modelled within the integrated assessment modelling framework of GCAM. GCAM is an energy sector-focused integrated assessment model incorporating complex interactions between the energy, land use and climate systems. The model is global in scale and GCAM-IIM version used in this study comprises 14 aggregate world regions with India as a separate region, and models energy and emissions in five yearly time steps from 2005 to 2095. GCAM-IIM disaggregates the Indian residential sector in urban and rural residential sectors, has a wider set of services than the core GCAM model and has assumptions on GDP growth aligned with Indian government documents. The modelling framework of GCAM models end use services in the building including commercial buildings; details of which can be found in Eom et al. (2012) and Chaturvedi et al. (2014). For information on other applications of GCAM, please refer to Clarke et al. (2008), Wise et al. (2009), Shukla and Chaturvedi (2012), Calvin et al. (2013), Zhou et al. (2013), Hejazi et al. (2014), Chaturvedi and Kim (2015), Fawcett et al. (2015) and Iyer et al. (2015). GCAM is an open-source model and has been developed by JGCRI, PNNL.

2.1.1 Estimating CO_2 emissions

GCAM, being a detailed energy sector model, endogenously calculates the energy consumption by fuel for different service categories in the commercial building sector as well as calculates the electricity supply mix. Details of modelling residential and commercial building energy demand for India can be found in Chaturvedi et al. (2014). Electricity is the only relevant fuel for commercial air conditioning and refrigeration, the technologies relevant for this study. We estimate indirect CO_2 emissions by multiplying the electricity consumption for RAC technologies with the average grid emission factor for the year in question, derived on the basis of electricity generation and associated emissions as determined endogenously in the model. We compare this with the direct HFC emission estimates as explained in the next section.

2.1.2 Estimating HFC emissions

HFC emissions from different sectors are calculated by emission factor approach. Generalised assumptions for leakage rates, during normal operation, servicing and disposal at end of

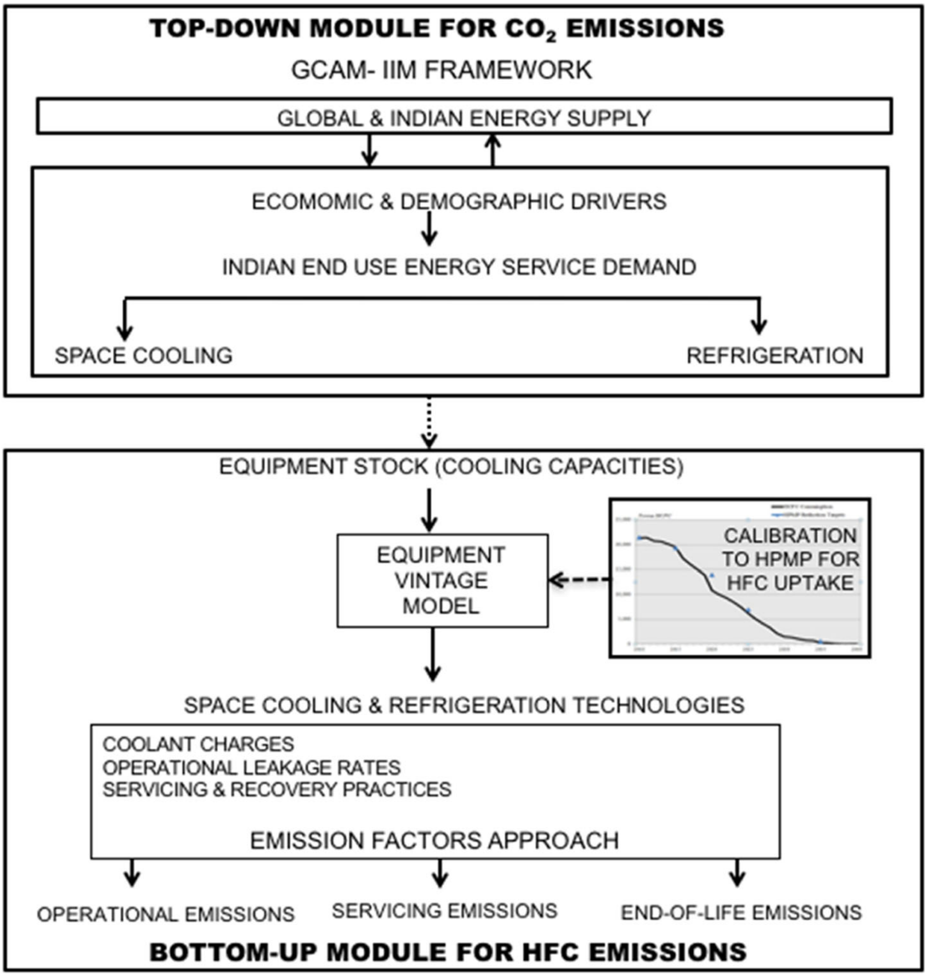

Fig. 1 Overview of methodology: coupling of integrated assessment modelling framework for CO_2 emissions with a bottom-up HFC emissions module

appliance or equipment life are used in absence of any national guidelines and reporting framework for HFC emissions. IPCC guidelines for emissions of fluorinated substitutes for ODSs (IPCC 2006) have largely been adapted for recent advancements and country-specific information. The emission factor approach is detailed under Appendix 1 of supplemental material, whereas assumptions on operational leakage rates under different scenarios, baseline HFC options and various emission/recovery factors are summarised in Tables A3, A6 and A7. These emission factors are sourced from product brochures for RAC equipment in India and sources[4] including IPCC/TEAP (2005), IPCC (2006), RTOC/UNEP (2006), RTOC/UNEP (2012) and TEAP/UNEP (2014). These assumptions are further validated though stakeholder interaction with various industry experts and members of research community and civil

[4] In absence of labelling of certain products for charge rates and credible information on leak tightness or operational leakage rate

society. This methodology has already been tested and proven for the Indian residential air-conditioning sector in Chaturvedi and Sharma (2016). Lower part of Fig. 1 gives an overview of various stages of the estimation process. Scope of emissions for this study is restricted to the use and end-of-life (EOL) phase for RAC equipment, and emissions during production, transportation and further distribution of chemicals are not under the scope. Additionally, leakages during equipment charging or recharging (initial charges at factory and subsequent servicing recharges) are ignored as their magnitude is understood to be relatively very low (IPCC 2006), both in India and globally, compared to emissions during the use and disposal of equipment utilising HFC coolants.

Under the BAU scenario, high GWP HFCs replace ozone-depleting substances (refer to Tables A6 and A7) as markets gradually transition to these options whilst meeting the national HPMP targets as outlined in the Ozone Cell (2013) report. We expect the commercial cooling applications to be based on HFC-410A and HFC-134a in the BAU world.[5] For commercial refrigeration, the key refrigerant in the BAU will be HFC-134a. Our choice of BAU refrigerants is based on the refrigerants being used in the developed world, as well as the direction in which Indian market is moving. We apply IPCC/AR4 GWPs over 100 years throughout this analysis (IPCC 2007). There can be alternative definitions of BAU as well that defines a future with different technological choices.

For understanding HFC emissions through the emission factor approach, we calculate the penetration of different types of commercial air-conditioning equipment (small direct-expansion (DX), medium-large DX and chillers) and refrigeration equipment (stand-alone units, display cabinets, remote condensers, vending machines, centralised systems). Detailed data, assumptions and approach for calculating the baseline floorspace, baseline electricity consumption, and future penetration and energy efficiency improvements of equipment are given in Appendix 2 and are based on information from RTOC/UNEP (2006), TERI (2006), Rue du Can et al. (2009), Knight Frank (2010), Kumar et al. (2010), RTOC/UNEP (2010), PwC (2012), UNEP (2012), Phadke et al. (2013), USAID and BEE (2014) and Waide et al. (2014).

In terms of per capita income, India's income grows from less than 1100 USD in 2010 to 1900 USD in 2020 and 12,000 USD in 2050 (all prices are in 2010 USD), which is very low compared to current per capita incomes in the developed countries. Population grows from 1.2 billion in 2012 to 1.53 billion in 2050. Along with these growth assumptions which form BAU scenario, we also explore the implications of a low economic growth scenario for India's HFC emissions. The GDP and population assumptions for both scenarios are summarised in Appendix 2, Table A1 of the Supplemental material. We align our GDP growth assumptions with the assumptions adopted by the NITI Aayog (National Institution for Transforming India, Government of India) for its energy scenarios. The NITI Aayog, in its reference (medium) and low-growth scenarios, assumes an average GDP growth of 6.7 and 5.8% per annum, respectively, between 2012 and 2047, which aligns well with our BAU and low-growth assumptions.

[5] A very small proportion of commercial equipment in India uses HFC-407A as well, exact estimation for which is not available. Due to very close GWPs, only HFC-410A is considered for the analysis

3 Results

3.1 Commercial floorspace expansion and growth in space cooling/refrigeration stock

The commercial floorspace in India is going to see huge growth in foreseeable future, and this is responsible for significant growth in installed capacity of commercial equipment for space cooling and refrigeration sectors. The total commercial floorspace (TCFS) in India is stipulated to grow from a half billion m^2 in 2005 to 10.6 billion m^2 in 2050 (Fig. 2a). Refer Chaturvedi et al. (2014) for details on modelling floorspace growth. A brief summary for modelling commercial floorspace is given in Appendix 1. In the past two decades, we have witnessed that the Indian service sector has grown much faster than the aggregate GDP and has been the main driver of India's GDP growth. Commercial sector floorspace is mainly dependent on how the service sector grows in an economy, and our future growth numbers reflect this trend of service sector growing at a pace higher than the aggregate GDP. Higher growth in the service sector is driven by growing per capita income as well as urbanisation. Indian average per capita income grows by 11 times between 2010 and 2050, and urbanisation rate increases to 53% in 2050 as compared to 30% in 2010. Requirement of space cooling equipment increases significantly as a result. Cooling requirement comes from a growth in cooling intensity (share of cooled floorspace in TCFS) itself with rising incomes and temperature in future. A combined effect of increasing TCFS and increasing cooling intensity results in even higher growth in total installed cooling capacity—from 52-GW cooling capacity in 2010 to 1489-GW cooling capacity in 2050 (Fig. 2b), which is twice the growth of TCFS in same period. Of this, medium-large DX and variable refrigerant flow (VRF) units take the highest share, followed by chillers and then small DX equipment. The penetration of room size air conditioners in commercial building sector is assumed to be negligible in 2050. Total commercial building stock is comprised of a variety of buildings[6] such as schools, offices, institutions, supermarkets, restaurants, hospitals and other public buildings with a widely varying range of demands for space cooling and refrigeration. Three commercial sub-sectors—offices, retail and hospitality—constitute large chunk of floorspace requirements throughout the time horizon. Our results on space cooling and refrigeration are reflective of this entire range of commercial floorspace, as a whole, from a macroperspective.

The demand for commercial refrigeration equipment grows even more drastically when compared to the commercial space cooling demand. It grows from nearly 1 million units in 2010 to nearly 26 million units in 2050 (Fig. 2c). These include stand-alone units, vending machines and remote condensing units. The supply chain of refrigerated goods has not matured in India, and as the market moves to centralised systems which are a preferred choice in supermarket buildings, the total number of installed centralised systems in the country are estimated to grow from 623 in 2010 to nearly 112,000 in 2050. The number of supermarkets and hypermarkets are estimated to grow from 587 and 32 in 2010 to nearly 100,000 and 6000, respectively, in 2050 (Fig. 2c), implying an average annual growth rate of 13–14%. Increasing urbanisation rate would mean a transition from rural informal commercial establishments to formal businesses and supply chains. With change in consumer preferences and food habits,

[6] Commercial buildings in India have an Energy Performance Index ranging from 200 to 400 kWh per m^2 per year (UNDP/GEF 2011)

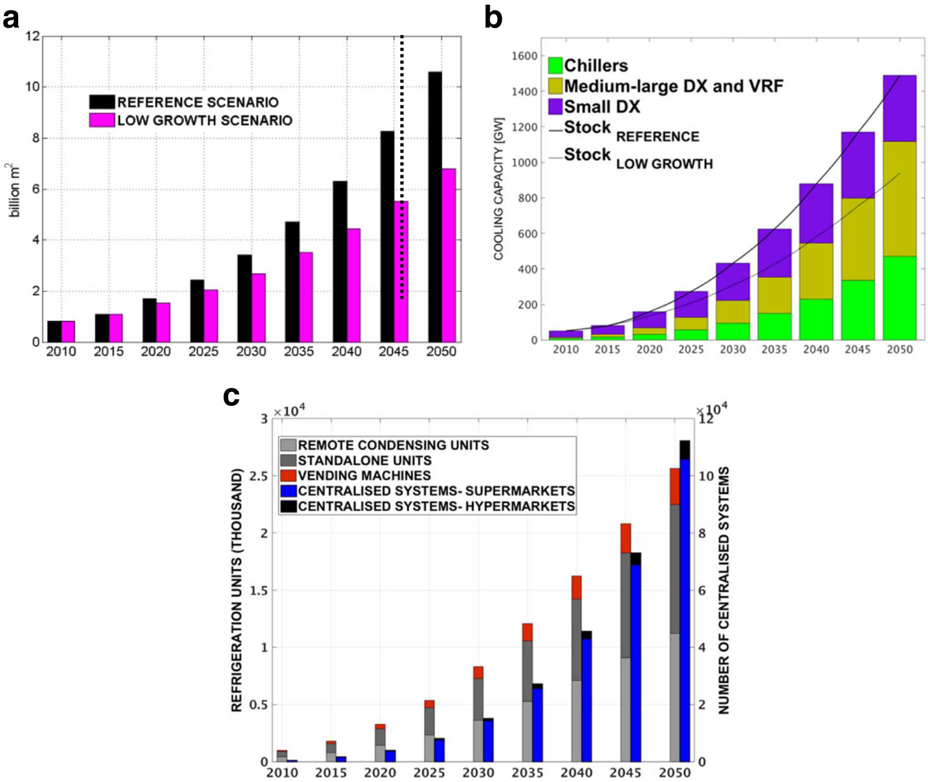

Fig. 2 **a** Modelled expansions in total commercial floorspace under BAU and low-growth scenario. **b** Associated growth in commercial cooling capacities including distribution amongst different types of equipment. **c** Growth in equipment stock for commercial refrigeration including different types of refrigeration units and centralised refrigeration systems

e.g. Indian market is already witnessing a move towards frozen foods especially in the urban areas, we can expect this category to grow significantly in the future.

3.2 Electricity consumption and emissions from commercial space cooling and refrigeration

Space cooling and refrigeration are energy intensive, and hence, major source of their GHG emissions is electricity consumption. Total electricity consumption as a result of these two activities in commercial buildings rises from 29.5 TWh in 2010 to 503 TWh in 2050. This contributes to 15% of commercial sector's total energy consumption in 2010 and grows to 29% in 2050. Two aspects of this growth need to be highlighted. First, the growth of commercial refrigeration is much faster than the growth of commercial air conditioning. Second, even though commercial air conditioning grows relatively slowly, its footprint in terms of electricity consumption is much larger than commercial refrigeration both now as well as in the long term. Electricity consumption for cooling commercial floorspace grows from 24 TWh in 2010 to 384 TWh in 2050 (Fig. 3a), whilst electricity consumption for commercial refrigeration grows from 5.5 TWh in 2010 to 119 TWh in 2050 (Fig. 3b).

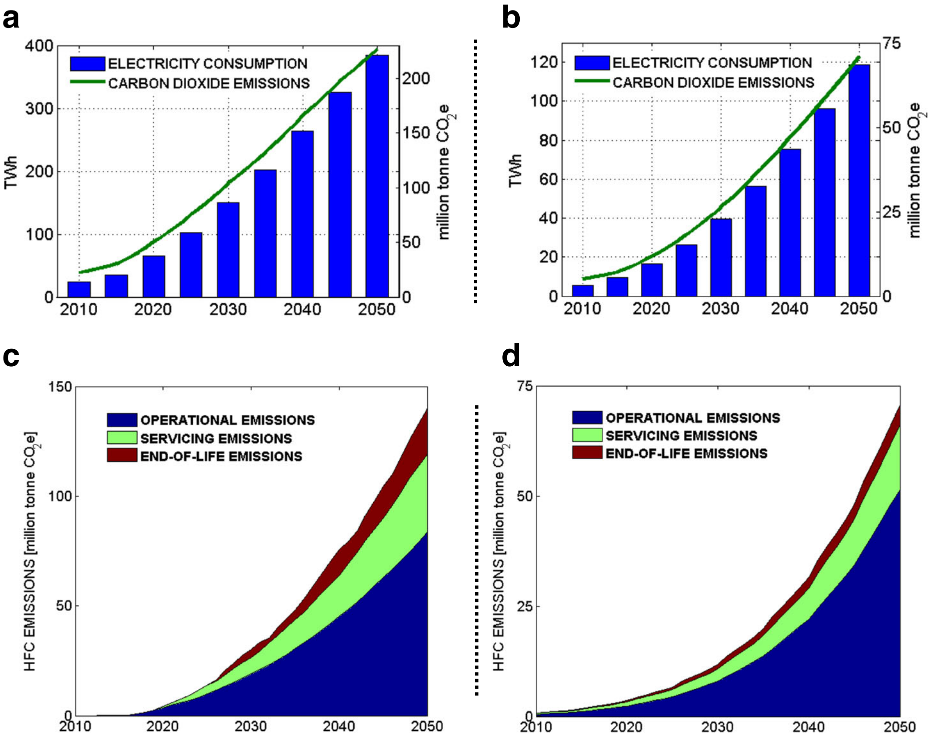

Fig. 3 **a** Long-term electricity consumption and CO_2 emissions from space cooling in commercial buildings. **b** Long-term electricity consumption and CO_2 emissions from refrigeration in commercial buildings. **c** HFC emissions from space cooling in commercial buildings. **d** HFC emissions from refrigeration in commercial buildings

CO_2 emissions resulting from electricity use in commercial space cooling and refrigeration grow significantly. For commercial cooling, emissions increase from 22 to 226 Mt CO_2e, and for commercial refrigeration, they increase from 5 to 71 Mt CO_2e. There are two key reasons for growth in indirect CO_2 emissions. First, the underlying service demand and resulting electricity consumption grow rapidly. Second, India's electricity generation mix in the BAU is heavily dependent on coal even till 2050, and hence, the carbon intensity of electricity generation changes only slightly between now and 2050. The effect of increasing penetration of cooling energy services during the period is to some extent offset by the energy efficiency improvements (100% energy efficiency improvement assumed between 2010 and 2050).

HFC emissions from commercial space cooling rise from a near zero in 2010[7] to 140 Mt CO_2e in 2050 (Fig. 3c) as a result of transition towards HFCs, whereas for refrigeration, they rise from 0.8 Mt CO_2e in 2010 to 71 Mt CO_2e in 2050 (Fig. 3d). Till now, mainly HCFCs have been used in India as refrigerants in these two sectors. As per India's reporting to ozone secretariat, HCFC consumption in India's air-conditioning sector was 8.2 Mt CO_2e in 2009; corresponding numbers for refrigeration were 0.7 Mt CO_2e. Reported data does not separate between residential, commercial and industrial sectors; only aggregate numbers are available. A bulk of HFC emissions in both the sectors are during operational leakages. Leakages are

[7] Prior to transition, only HFC-134a is being utilised for a very small segment of the market, i.e. very large sized centrifugal chillers

higher in the case of centralised refrigeration systems compared to the commercial cooling equipment. GHG emissions (including CO_2 and HFC) from space cooling and refrigeration surge from 28 Mt CO_2e in 2010 to 508 Mt CO_2e in 2050 (18-fold increase in total GHG). By 2050, equipment stock consists of only HFC-based equipment in BAU scenario and results indicate that contribution from HFC to total GHG emission for commercial space cooling and refrigeration is 38% and 50%, respectively.

Velders et al. (2015) estimate that India's total HFC emissions in 2050 will be 400 Mt CO_2e. Velders et al. (2015) does not discuss sector-specific emissions, e.g. residential or commercial sector HFC emissions. Their classification is rather based on type of equipment, e.g. stationary or mobile ACs, wherein residential, industrial and commercial air conditioning and refrigeration are classified under the same category. A direct sector-level comparison is therefore not possible. Our approach is bottom-up, where India specific higher leakage rates and economic growth rate are used, which explain the higher emissions. These rates have been validated with Indian industry and experts. Chaturvedi et al. (2015), based on a bottom-up approach, estimate India's HFC emissions in 2050 to be 500 Mt CO_2e. Commercial building sector HFC emissions as presented in our study are 42% of India's total HFC emissions in 2050 as estimated in Chaturvedi et al. (2015).

Total HFC emissions from commercial refrigeration and air-conditioning sectors are estimated to grow from 1 Mt CO_2e in 2010 to 211 Mt CO_2e in 2050 in this study that is in agreement with total HFC emissions from commercial RAC sector of 210 Mt CO_2e in 2050 estimated by Purohit and Höglund-Isaksson (2017). However, Purohit and Höglund-Isaksson (2017) have different estimates for individual sectors primarily due to different modelling assumptions.

3.3 Sensitivity analysis for emissions by sectors

Economic growth and operational leakage rates are two key variables which impact the trajectory of CO_2 and HFC emissions estimated in this study. In the past 20 years, economic growth in India has fluctuated widely. Growth slowly started picking up by mid-1990s; however, there was a dampening impact of the East Asian crisis by the end of last century. Post that period, the benefits of economic reforms started becoming evident and Indian real GDP growth reached a high of over 9% for three consecutive years after 2005. Post-2010, this growth rate however decelerated to below 5% in 2014–2015 due to international economic conditions as well as stalling of domestic economic reforms within the country. Growth rate has already started picking up with expectations of a new set of economic reforms. Analysts and experts expect growth to move beyond 8% in the next 5 years, and this is what our BAU scenario reflects. However, past experience has shown us that economic growth can also slowdown, which will impact our results of future emissions. CO_2 emissions from both the sectors are lower by 37% in 2050 relative to the BAU scenario. This implies a combined decline in CO_2 emissions by 110 Mt CO_2e in 2050. Though CO_2 emissions are lower, we find a significant increase in the uptake of commercial cooling and refrigeration and resultant CO_2 emissions even under a low-growth scenario.

As in the case of CO_2 emissions, we find that HFC emissions will also increase significantly with a low income growth and will grow to a value which is 37% lower (including space cooling and refrigeration) than the BAU scenario in 2050. This is 89[8] Mt CO_2e lower for

[8] cf. 140 million tonne CO_2e under BAU scenario

space cooling and 43[9] Mt CO_2e lower for refrigeration as compared to the BAU growth scenario. As the entire stock of equipment declines proportionately with the lower growth, the CO_2 emissions from electricity use also decline proportionately, and therefore, share of HFC emissions in overall GHG emissions will remain same irrespective of growth scenario. The CO_2 intensity of electricity generation remains similar in both high- and low-growth scenarios.

For a given growth trajectory, HFC emissions also vary widely with leakage rates. Leakage rates determine the fugitive emissions from equipment, and based on this, number of recharges that will be required over the life of equipment. In BAU scenario, we assume that leakage rates will stand as they do to the best of our understanding but an improvement or worsening of leakage in future could change the HFC emission trajectories, and it is therefore important to assess their impact on emissions. We perform sensitivity analysis over a range of leakage rates—low, medium/reference and high. Uncertainty analysis on leakage rates shows that HFC emissions from space cooling in 2050 could be anywhere from 72 to 192 Mt CO_2e depending upon presence or absence of a regulation governing management of HFC gases and penetration of leak tight technologies. Similarly, for refrigeration, same might vary from 46 to 91 Mt CO_2e. This means that depending upon the leakage rates, contribution of HFC in overall GHG emissions for commercial space cooling and refrigeration varies between 24–46 and 39–56%, respectively.[10]

There are some mid-GWP alternatives being discussed for the commercial air-conditioning sector. Two of these, HFC-32 and DR-55, are mid-GWP alternatives, with GWPs around 675. If the commercial AC industry moves towards either of these instead of HFC-410A, the HFC emissions from this sector in 2050 will be less than 50 Mt CO_2e, as against 140 Mt CO_2e. However, by definition, any move away from high GWP alternatives is not BAU.

3.4 Implications of the Kigali Amendment and best practices

Kigali Amendment to the Montreal Protocol was signed by parties in October 2016 for limiting use of HFCs as refrigerants. As per the agreement, India will need to freeze its HFC consumption in 2028, and will have to reduce it to 15% of the baseline by 2050. The baseline for India is the average HFC consumption of 2024–2026 plus 62.5% of 2009–2010 HCFC consumption. The quantum of direct HFC emissions mitigated will depend on the timing of transition in the commercial cooling and refrigeration sectors. For example, in 2028, India can choose either of commercial cooling, residential cooling or mobile air-conditioning sectors as the first step towards the long-term transition. HFC emission reduction from any sector will depend on when that sector starts transitioning. We present estimates below for three different scenarios reflecting this variation in mitigation depending upon time when their use is controlled for commercial sector. It should be noted that cumulative emissions from commercial space cooling and refrigeration in the reference scenario during 2010–2050 are 1782 and 833 Mt CO_2e, respectively (Table 1).

Based on our sensitivity analysis on leakage rates, we also estimate the implication of moving towards best management practices for minimising operational leakages. We estimate the mitigation potential through best practices as the difference between the 2020 and 2050 HFC emissions in our reference leakage rate scenario and low operational leakage rate scenario. If India adopts best practices by 2020 and average operational leakages are

[9] cf. 71 million tonne CO_2e under BAU scenario
[10] From electricity use in commercial RAC equipment

Table 1 Emission mitigation from commercial space cooling and refrigeration sectors under different control periods

Control period	Cumulative emission mitigation (Mt CO_2e)	
	Commercial space cooling	Commercial refrigeration
2030–2050	1637	747
2035–2050	1453	672
2040–2050	1158	549

minimised, HFC emissions in the commercial cooling and refrigeration sectors can be reduced by 50 and 35%, respectively, between 2020 and 2050, a significant benefit of adopting best practices. We highlight here that along with minimising leakages during operations, if end-of-life emissions are also minimised through collection of managed disposal of discarded air conditioners and refrigeration equipment, HFC emissions would further decline.

4 Conclusion and discussion

Direct and indirect emissions from the commercial building sector in India are expected to increase significantly with increasing incomes and urbanisation. Research on estimating future trajectories of emissions for this sector is however conspicuous by its absence. For guiding policy interventions to mitigate its potential GHG impact, it is critical to understand the potential trajectory of energy use and emissions from the commercial building sector in India. We contribute to this understanding through our detailed modelling of energy consumption and resultant direct and indirect emissions from space cooling and refrigeration applications for the commercial building sector in India. We focus on direct HFC emissions and indirect CO_2 emissions due to electricity use. It is the first such attempt in our knowledge to undertake a detailed modelling of commercial cooling and refrigeration for India. We hope that more research is undertaken on the Indian commercial sector in future so that understanding of this sector improves.

We find that if India follows the same path as the west, total GHG emissions from space cooling and refrigeration in commercial buildings will increase significantly to 508 Mt CO_2e/year in 2050. Of this, direct HFC emissions will be 40%. This is similar to the share of direct HFC emissions in the total GHG emissions of India's residential air-conditioning sector (~36%) as shown by Chaturvedi and Sharma (2016). Space cooling and refrigeration in commercial spaces are energy intensive. Their aggregate CO_2 emissions[11] are expected to rise more than tenfold from 2010 to 2050. This reflects the huge increase in the electricity demand for these technologies to 503 TWh in 2050 by over 15 times between 2010 and 2050.

Commercial sector presents significant challenges for mitigation of high GWP HFCs in India as the number of option available for high ambient conditions are limited due to large charge requirements of commercial equipment. In the BAU scenario, the Indian commercial sector is expected to move towards high GWP refrigerants HFC-134a, HFC-410A and HFC-404A. These refrigerants are commonly used in the industrialised countries as of now. If near-zero GWP refrigerant options such as hydrocarbons (HCs) and hydrofluoroolefins (HFOs) are extended to these applications, it could translate into roughly 40% reduction in GHG emission intensity of RAC applications where their use becomes feasible. Mixes of HFCs and HFOs

[11] From electricity use in commercial RAC equipment

also present a significant potential for almost 20% GHG reductions (assuming a 50% HFC + 50% HFO mix). Cost of these options could be a major challenge for India as IPR costs constitute a majority of cost for such options.

Another important insight that comes out of our research is the role of best practices and capacity building for mitigating emissions during servicing and at the end of life. Emissions during both these stages lead to a bulk of direct emissions. Capacity building for minimising leakages, recovery and reuse of refrigerants needs to be undertaken. Large charge sizes present a significant opportunity for cost-effective recovery, reutilisation and management of such gases in large applications. India already has a 'Skill India Mission' under which technicians can be trained to recover and reuse refrigerants. The Multilateral Fund (MLF) of the Montreal Protocol could also support this training process in developing countries.

Improvement in energy efficiency is an important concern. India has a very strong thrust on energy efficiency in end-use applications. Our analysis assumes significant improvements in the energy efficiency of space cooling and refrigeration based on the attention of Indian policy makers this issue has garnered. Such improvements are critical as in absence of this the indirect CO_2 emissions will only increase. The transition towards a low GWP alternative should also be guided by the energy efficiency of the alternative. Of course, the role of electricity generation mix can change the outcome significantly. Our analysis focuses on the BAU under which coal is the mainstay of India's electricity generation even in the long run. If India achieves the target 40% share of non-fossil electricity generation capacity specified under its Intended Nationally Determined Contributions (INDCs), which are contingent on technical and financial assistance (UNFCCC 2015), then the indirect emissions from the commercial sector will itself decline. Analysis of emission intensity of grid under INDCs is outside the scope of our study, and hence, we focus on the BAU which is the direction in which Indian electricity generation is expected to evolve in absence of any policy push.

Parties to the Montreal Protocol have agreed to phase down high GWP HFCs. This will send a strong signal to all the Indian stakeholders that eventually all the sectors will have to phase down these refrigerants. The commercial sector is one of the key sectors that will have to transition towards low GWP alternatives. Funding support from the MLF will help the Indian stakeholders in this transition. A landmark deal on HFC phase-down at Kigali will undoubtedly accelerate a global transition in the commercial building sector in India and across the world towards low GWP alternatives and will have an important impact on global efforts to mitigate climate change.

Acknowledgements We would like to thank the Ministry of Environment, Forest and Climate Change (MoEFCC), Government of India, for their comments on our work. We would like to acknowledge support of Indian industry especially the Voltas, Toro Cooling Systems, Daikin India, and independent experts Mr. Kapil Singhal, Dr. Radhey Agarwal and Dr. Sukumar Devotta for sharing information and insights on space cooling and refrigeration equipment in commercial buildings in India. We thank Dr Arunabha Ghosh (CEEW), Prof P R Shukla (IIM Ahmedabad) and Prof Amit Garg (IIM Ahmedabad) for their feedback on our HFC emissions modelling research. We are thankful to Shakti Sustainable Energy Foundation for the financial assistance to modelling research on estimating India's HFC emissions. Finally, we thank the Joint Global Change Research Institute/Pacific Northwest National Laboratory, USA, for the access to the GCAM modelling framework.

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