Co-benefits of energy-efficient air conditioners in the residential building sector of China

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Abstract

Electricity demand for room air-conditioners (ACs) is growing significantly in China in response to rapid economic development and mounting impacts of climate change. In this study, we use the bottom-up model approach to predict the penetration rate of room ACs in the residential building sector of China at the provincial level, with the consideration of the urban-rural heterogeneity. In addition, we assess co-benefits associated with enhanced energy efficiency improvement of AC systems and the adoption of low global warming potential (GWP) refrigerants in AC systems. The results indicate that the stock of room ACs in China grows from 568 million units in 2015 to 997 million units in 2030 and 1.1 billion units in 2050. The annual electricity saving from switching to more efficient ACs using low-GWP refrigerants is estimated at almost 1000 TWh in 2050 when taking account of the full technical energy efficiency potential. This is equivalent to approximately 4% of the expected total energy consumption in the Chinese building sector in 2050 or the avoidance of 284 new coal-fired power plants of 500 MW each. The cumulative CO_2eq mitigation associated with both the electricity savings and the substitution of high-GWP refrigerants makes up 2.6% of total business-as-usual CO_2eq emissions in China over the period 2020 to 2050. The transition towards the uptake of low-GWP refrigerants is as vital as the energy efficiency improvement of new room ACs, which can help and accelerate the ultimate goal of building a low-carbon society in China.

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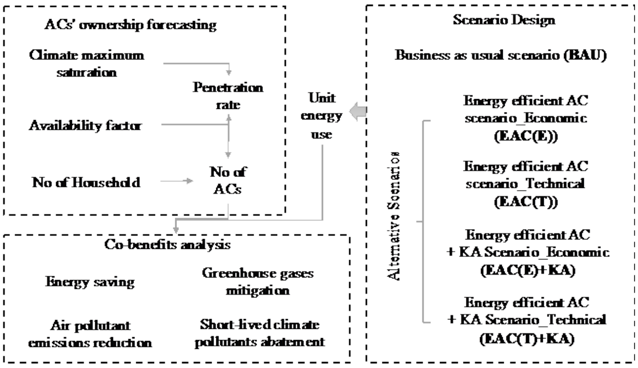

1. INTRODUCTION

The global energy consumption of space cooling in the building industry is growing faster than in many other industries[1] (i.e. transportation industry and manufacturing industry) and has more than tripled between 1990 and 2016[2]. The increase is expected to continue in the next few decades[3-6]. Space cooling is expected to account for an ever-increasing share of energy use with particularly strong growth in emerging economies. Until 2050, the three countries China, India, and Indonesia alone will account for half of the global growth in cooling energy demand [2,7]. Over the last two decades, China noted the fastest growth worldwide in energy demand for space cooling in buildings, increasing at 13% per year since 2000 and reaching nearly 400 terawatt-hours (TWh) of electricity consumption in 2017 [8]. The increase in energy consumption since 2000 is driven by increasing income and growing demand for thermal comfort. As a result, space cooling accounted for more than 10% of total electricity consumption in China since 2010 and around 16% of the peak electricity load in 2017 [8]. Cooling-related carbon dioxide (CO_2) emissions from electricity consumption consequently increased fivefold between 2000 and 2017 [8], given the strong reliance on coal-fired power generation in China. Already, China is the country worldwide with the largest production and use of air conditioners (ACs), as the country manufactured around 70% of total world output and consumed approximately 40% of global AC sales in 2017 [8-10]. The penetration rates of room ACs in China have increased from around 20% in 1997 to about 130% in 2018 for urban residential buildings and from below 1% in 1997 to around 50% in 2018 for rural residential buildings [11] (see: Figure S1 of the SI). To alleviate the pressures of energy consumption and associated greenhouse gas (GHG) and air pollutant emissions brought about by the increase in space cooling demand, China has released a series of household energy efficiency standards since 1989 [12-16] (see: Table S1). However, the energy efficiency of the units sold in the market differs enormously [2, 8] (see: Figure S2). Currently, the average energy efficiency of room ACs sold is 60% less than the efficiency level of the best available technology and 20% lower than the average technology level available in China [8]. At the provincial level, penetration rates of room ACs for urban and rural areas are presented in Figure S3 of the SI.

A review of the literature indicates that there is a large potential for the usage of more energy-efficient ACs in the building sector. The application of energy-efficient ACs has significant potential for electricity savings and associated reductions in GHG and air pollutant emissions [2, 8, 17-21]. According to the recent Scientific Assessment of Ozone Depletion[22], an energy efficiency improvement of 30% in mini-split ACs is estimated to be technically and economically feasible as well as cost-effective in many economies [22]. At the global level, the International Energy Agency (IEA) estimated that under a baseline scenario the energy requirements of space cooling would triple by 2050, reaching 6200 TWh per year, whereas in an efficient cooling scenario only 3400 TWh per year would be required, which is 45% lower than that in the baseline [2]. This saving potential is equivalent to the total electricity consumption of the European Union in 2016. At the regional level, Grignon-Masse et al. (2011) assessed the environmental impacts of energy-efficient European ACs using a lifecycle analysis approach[76]. Borg and Kelly (2011) focused on the electricity consumption and peak load impacts of appliance efficiency improvements in European households[77]. At the national level, several studies evaluated the energy savings, emissions reductions, and economic benefits related to energy-efficiency standards and improvements for ACs and other appliances. Rosas-Flores et al. (2011) estimated the energy savings and CO_2 emission reduction potentials of urban and rural household appliances, including ACs, in Mexico[78]. Cardoso et al. (2012) employed a bottom-up model to evaluate the impacts of energy-efficient ACs in Brazil on electricity savings and GHG mitigation [17]. Based on the estimation of the quantity of equipment in use and the energy consumption per unit equipment, they concluded that an annual electricity saving of 322 GWh per year could be obtained from a switch to energy-efficient ACs in Brazil. Phadke et al. (2014) estimated the electricity demand of room ACs in India by 2030 considering factors such as climate change and income growth using market data on the penetration of ACs in different income classes and climatic regions [23]. The total electricity saving potential from efficient room ACs using the best available technology would reach over 118 TWh in 2030 in India with potential peak demand saving found to be 60 GW. This is equivalent to avoiding 120 new coal-fired power plants of 500 MW each. McNeil et al. (2019) analyzed the impact of energy-efficient appliances on Indonesia's peak load, finding that ACs will be the main driver of peak growth by 2025[79]. Similarly, IEA (2019) explored the major trends and challenges brought about by the rapid uptake of room ACs in China. The findings indicated that greater affordability, climate change, as well as changing occupant behavior would significantly increase cooling energy use [8]. IEA (2019) concluded that the annual energy demand would be 200 TWh lower in 2030 under the efficient cooling scenario relative to the baseline scenario. Another recent study by Karali et al. (2020) modeled the costs and benefits of recently proposed new room AC minimum energy performance standards (MEPS) in China and observed that the new standards would bring cumulative CO_2 reductions of 12.8% between 2019 and 2050[80].

Furthermore, the benefits of switching to new energy-efficient ACs are not only coming from the efficiency improvement caused by the AC system (e.g. more efficient compressors, heat exchangers, etc.), but also from the replacement of high global warming potential (GWP) refrigerants used as coolants in ACs [24-26]. Normally, the refrigerants e.g., chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs), are thousands of times more powerful GHGs than CO_2 on a mass-equivalent basis[27, 28] (see details in Section S3 of SI). While the use of CFCs has been successfully phased-out, HCFCs are currently in the process of being phased-out under the Montreal Protocol [29]. The ban on the use of CFCs in developing countries following the Montreal Protocol was fully implemented in 2010[30], with China having implemented it ahead of schedule in 2006 [31], however, full enforcement may yet to be completed [86]. The Kigali Amendment (KA) to the Montreal Protocol adopted in October 2016 and has entered into force in January 2019, is a global agreement to phase-down the consumption of HFCs by 2050 [32]. The KA aims to limit and eventually significantly reduce emissions of HFCs through a differentiated phase-down of HFCs across countries over the next three decades. The associated conversion of equipment from appliances using HFC refrigerants with high GWPs to low GWP refrigerants provides an unprecedented opportunity to consider other possible technological improvements that can offer additional climate co-benefits. The use of low GWP refrigerants as a replacement for conventional HFCs offers an opportunity to redesign the equipment with improved energy efficiency. In the literature, few attempts have been made to assess the impact of enhanced energy efficiency improvement of AC systems and transitions to low-GWP refrigerants. Höglund-Isaksson et al. (2017) analyzed the global abatement costs of achieving the substantial reductions in HFC consumption agreed in the KA and incorporated possible energy efficiency improvements when using alternative substances and technologies to switch away from HFCs[33], however, without considering the impact from simultaneously improving the AC system (heat exchangers, compressors, valves, etc.). Similarly, Purohit et al. (2018) analyzed the impacts of the KA to phase-down HFCs in Asian countries [34]. These studies find that full compliance with the KA could save about 3000 TWh of electricity in Asian countries over the period 2018 to 2050 due to a transition to appliances using low-GWP refrigerants. This corresponds to an estimated 0.5% of expected cumulative electricity consumption in Asia over the same period. In contrast, IEA (2018) assessed the energy efficiency improvement due to enhanced AC systems[2], however, without explicitly considering efficiency improvements from the transition to low-GWP refrigerants as such. In a recent study, Purohit et al. (2020) account for both types of energy efficiency enhancements and find that if technical energy efficiency improvements are fully implemented together with the HFC phase-down under the KA, the resulting electricity savings could exceed a fifth of expected future global electricity consumption[47].

The distinction between top-down and bottom-up model approaches is interesting because they can sometimes produce opposite outcomes for the same problem. Grubb et. al. (1993) state that the top-down approach is associated with –but not exclusively restricted to - the "pessimistic" economic paradigm, while the bottom-up approach is associated with the "optimistic" engineering paradigm[84]. The building stock energy models use both top-down and bottom-up approaches [85]. The top-down methods start with the aggregated energy consumption for a given region and time, then disaggregate into sectors according to e.g., building function or spatial proximity, and typically factor in the interrelationships between the energy sector and other variables such as economic and technological factors. The bottom-up methods work at an individual level calculating the energy consumption of individual end-uses (e.g. cooking, heating/cooling, lighting) or buildings, then summing them up to represent the required region. It may be noted that the bottom-up approach is commonly used in co-benefits estimation as it e.g., allows for simulating a partial market equilibrium with fixed relative prices [82], identifying least-cost technology mixes for exogenous demand, and/or simulating specific sectoral policies by setting exogenous environmental constraints [83]. In this study, we have used a bottom-up engineering approach to model the stock of room ACs and assess the co-benefits without considering the extended impacts e.g., on relative prices and equilibrium in the energy market. Climate and air pollution co-benefits of space cooling in the Chinese residential building sector are assessed by taking account of a) regional and urban/rural heterogeneities (including macroeconomic factors, geographic, demographic factors, household structure, etc.) and climatic zone differences among provinces across China; and b) technical and economic energy efficiency improvements of AC system (i.e., heat exchangers and compressors) and the transition towards low-GWP refrigerants.

2. MATERIALS AND METHODS

In accordance with a bottom-up approach, co-benefits of the uptake of energy-efficient ACs in the Chinese residential building sector by 2050 are assessed in a four-step procedure. First, the ownership of room ACs by Chinese households is projected considering regional and urban/rural heterogeneities (including macroeconomic/demographic factors, and household structure, etc.) and changing climatic conditions (measured by cooling degree days, CDDs). In a second step, the unit energy consumption (UEC) of room ACs is estimated as a function of CDDs and household income levels to assess the energy consumption in the business-as-usual (BAU) scenario. In a third step, two sets of alternative scenarios are developed: a) considering only the technical and economic UEC potentials due to enhanced energy efficiency of the room ACs, and b) taking into account both the transition towards low-GWP refrigerants and the technical and economic UEC potentials. Finally, co-benefits in terms of reduced GHG and air pollutant emissions are estimated using the electricity savings derived from the alternative scenarios.

2.1 Modeling Ownership of ACs

To estimate the number of room ACs in the Chinese residential building sector, we assume that both energy consumption per unit and the proportion of households owning air-conditioners (penetration rate) depend on the climatic condition and income level[35], both being higher in warmer and wealthier places (e.g. urban areas in warm regions). The penetration of ACs in a province is formulated as a function of the climate maximum saturation (CMS) for that province and of the percentage of the CMS attained at that time in the region (availability) as shown in Eq. (1).

$$PR_{i,t} = CMS_{i,t} \times AF_{i,t} \quad (1)$$

where $PR_{i,t}$ represents the penetration rate of room ACs in the i^{th} province in t^{th} year, $CMS_{i,t}$ the climate maximum saturation in the i^{th} province in t^{th} year, and $AF_{i,t}$ the availability of the i^{th} province in the t^{th} year.

CMS is derived from the assumption that the maximum penetration rate is the maximum saturation for a climate with a given amount of CDDs[35]. The relationship between maximum saturation and CDD is exponential, as developed by Sailor and Pavlova (2003) [36] for 39 cities in the United States and modified by McNeil and Letschert (2008) [35] for developing countries (including China) as shown in Eq. (2).

$$CMS_{i,t} = 1 - 0.949 \times \exp\left(-0.00187 \times CDD_{i,t}\right) \quad (2)$$

The availability of ACs as a function of household income (HHI) is assumed to develop along a logistic function [35, 38], with a threshold point beyond which ownership increases rapidly [37-40], as shown in Eq. (3):

$$AF_{i,t} = \frac{\alpha_{i,t}}{1+\gamma_{i,t}\exp\left(-\beta_{i,t} \times HHI_{i,t}\right)} \quad (3)$$

where $\alpha_{i,t}$ is the maximum value of $AF_{i,t}$, together with $\beta_{i,t}$ and $\gamma_{i,t}$ being regression coefficients estimated for the $AF_{i,t}$ of each province.

Further details and data sources on CDDs, macro-economic parameters at the provincial level, and availability of room air-conditioners are provided in Section S2 of the SI.

2.2 Unit Energy Consumption

The energy consumption of ACs is not only related to the ownership and CDDs but also the income level of the household. Due to the high electricity consumption of ACs, wealthy households are likely to use it more frequently and for longer periods, while low-income households, despite owning ACs, will use it occasionally when necessary [8, 35, 39]. Hence, consistent with the method used in McNeil and Letschert (2008) [35] and Kitous and Després (2018) [39], we set the model of unit energy consumption (UEC) of AC as a function of the climatic conditions (i.e. CDDs) and the household income (HHI) level, as shown in Eq. (4).

$$UEC = 410 \cdot \ln(CDD) + 0.033 \cdot \ln(CDD) \cdot HHI - 2577 \qquad (4)$$

To assess UEC we have used historical data obtained from Mendes et al. (2014) [41] and Guo et al. (2017) [42] for 11 provinces in different climatic zones of China (see Figure S4 of the SI).

2.3 Scenarios Design

Apart from the BAU scenario, we have developed four alternative scenarios (see Figure S5) to assess the electricity savings and co-benefits associated with enhanced energy efficiency improvements of AC systems and a transition towards low-GWP refrigerants. The first two alternative scenarios only consider the technical and economic efficiency improvement due to the AC system optimization (e.g. using efficient compressors, heat exchangers, valves, etc.), while the last two alternative scenarios consider both the technical/economic energy efficiency improvement of ACs and the energy efficiency improvement from transitioning to a low-GWP refrigerant (i.e. HC-290, GWP_{100} = 1)[22] from high-GWP HFCs (i.e. HFC-410A, GWP_{100} = 1924 or HFC-32, GWP_{100} = 677) [45], as required to comply with the KA (see Section S3 of the SI). In the economic energy-efficient AC scenario “EAC(E)”, the UEC improvement is set to 30%, and in the technical energy-efficient AC scenario “EAC(T)” the energy efficiency improvement is set to 60% [43, 47]. The energy efficiency improvement is 36% in the economic energy-efficient AC plus transition towards low-GWP refrigerants named as “EAC(E)+KA” scenario, whereas the energy efficiency improvement is assumed to 72% in the technical energy-efficient AC plus transitioning towards low-GWP refrigerants [23, 44, 47] named as “EAC(T)+KA” scenario (See details in Table 1).

In consistency with assumptions in Purohit et al. (2020), the estimated electricity saving potential in 2025 and 2030 is constrained by inertia in technology uptake resulting in a gradual phase-in of new technology and with maximum applicability only assumed possible from 2035 onwards[47].

2.4 Co-benefits analysis

The methodology for estimating co-benefits in terms of electricity savings and the associated reduction in GHGs and air pollutants is described in Section S4 of the SI. In the BAU scenario, total energy consumption in room ACs is estimated using the number of households, the penetration rate of room ACs (Eq. (1)), and UEC (Eq. (4). The electricity savings in the alternative scenarios are estimated using different energy efficiency assumptions (technical and economic energy efficiency potential) due to systems improvement and transition towards low-GWP refrigerants under the KA. The technical and economic efficiency gains calculated are from improvements in the equipment (heat exchangers, compressors, valves etc.) and using low-GWP (e.g. HC-290) refrigerants. The Greenhouse gas - Air pollution Interactions and Synergies (GAINS) model developed by IIASA [46] contains a database on emission factors for a range of air pollutants and GHGs from global energy consumption. From this database, we take the implied emission factors for CO_2, CH_4, air pollutants (sulfur dioxide, SO_2; nitrogen oxides, NO_x; and fine particulate matter, $PM_{2.5}$), and short-lived climate pollutants (SLCPs) (e.g. black carbon, BC; and organic carbon, OC) that reflect the expected region/province- and year- specific fuel mixes used in power plants in the IEA’s World Energy Outlook (WEO) 2018 Current Policies Scenario (CPS), New Policies Scenario (NPS) and Sustainable Development Scenario (SDS), respectively, in the timeframe to 2050 (see Figure S6 for details). The CPS scenario only considers the impact of those policies and measures that are firmly enshrined in legislation as of mid-2017. It provides a cautious assessment of where momentum from existing policies might lead the energy sector in the absence of any other impetus from the government. The NPS scenario provides a sense of where today's policy ambitions seem likely to take the energy sector. It incorporates not just the policies and measures that governments around the world have already put in place, but also the likely effects of announced policies, including the Nationally Determined Contributions (NDCs) made for the Paris Agreement (PA). The SDS scenario outlines an integrated approach to achieving internationally agreed objectives on climate change, air quality and universal access to modern energy. It represents a low carbon scenario consistent with a 2^{o}C (i.e., 450 ppm) global warming target for this century, with considerably lower air pollution.

Table 1. Overview of energy efficiency scenarios for room ACs

S. No.	Scenario	Description
1	Business as usual -- BAU	Unit energy consumption (UEC) will remain at the 2015 level.
2	Efficient room AC (Economic) -- EAC(E)	Economic potential of UEC - efficiency of room AC unit will improve by 30% [43].
3	Efficient room AC (Technical) -- EAC (T)	Technical potential of UEC - efficiency of room AC unit will improve by 60% [47].
4	Efficient room AC (Economic) + Kigali Amendment -- EAC(E)+KA	Economic potential of UEC along with additional energy efficiency improvement of 6% due to low-GWP refrigerants (i. e. HFC-32, HC-290).
5	Efficient room AC (Technical) + Kigali Amendment -- EAC (T)+KA	Technical potential of UEC along with additional energy efficiency improvement of 12% due to low-GWP refrigerants (i. e. HFC-32, HC-290).

3. RESULTS AND DISCUSSION

We assess the energy sector and environmental co-benefits of the phase-down of HFCs used in room ACs in the Chinese residential building sector under different scenarios using the methodology presented in Section 2. In the following sub-sections, we present the modeling results of the projection of room ACs in China at the national and provincial levels. In comparison to the BAU scenario, the electricity saving potentials under different scenarios have been estimated along with abatement potentials of GHGs, air pollutions and SLCPs until 2050.

3.1 BAU projections of room ACs in China

The total production volume, export volume, domestic retail volume of the Chinese room AC market from 2003 to 2017 is shown in Figure S1. The annual domestic sales volume of ACs has grown steadily, from 20 million units in 2003 to 88 million units in 2017, an increase by more than seven times [11]. The historical penetration of room ACs in Chinese provinces is taken from the National Bureau of Statistics of China [11] as shown in Figure S3. The macro-economic parameters (including GDP, population, etc.) are taken from NBSC (2019) [11] whereas the urbanization rate at the national level is taken from UN DESA (2018) [48]. The historical data on average household sizes across the Chinese provinces is taken from the Institute of Population and Labor Economics of China [49-51], whereas the future projections are taken from Zeng et al. (2008) [52] due to the unavailability of recent household size projections at the provincial level. The CDD is the most common climatic index used to assess impacts on demand for space cooling services and reflects the deviation between the average temperature and a specified base temperature. The definition of CDDs involves determining a temperature threshold for AC employment, which varies due to differences in human physiological needs, energy supply, economic level, temperature characteristics and so on. For example, the threshold temperatures for CDD employment are 23 °C in Spain [53], 22 °C in Europe [54], and 18.33 °C for the United States [55]. The base temperature used for China differs across studies [56-60] and is for this study taken to be 18 °C. The BizEE Degree Days Weather Data for Energy Professionals is used to calculate the average CDDs during the last five years of each province. This data is taken to be the historical CDD for the year 2015 (see Table

S2). The trend projection of CDDs for China at the national level until 2050 is obtained from IEA (2018) [2]. Due to the lack of availability of provincial level projections of CDDs, we assume the same trend applies to provinces as the national level of China.

Using the modeling framework discussed in the methodology section (Section 2), the results indicate that the stock of room ACs in the residential building sector of China grows from 568 million units in 2015 to 997 million units in 2030 and 1.1 billion units in 2050. In urban China, room AC ownership per 100 households increases from 114 units in 2015 to 219 units in 2030 and 225 units in 2050. The overall growth in the number of installed room ACs remains relatively slow from 2040 onwards due to saturation amongst urban households. In rural areas, room AC ownership per 100 households increases from 48 units in 2015 to 147 units in 2030 and 208 units in 2050 due to the increasing wealth of rural households. The number of room ACs in urban China increases from 486 million units in 2015 to 793 million units in 2030 and 919 million units by 2050. For rural China, the corresponding numbers are 82 million units in 2015, 218 million units in 2040 and 208 million units in 2050 with a slight decline in the last years due to rapid urbanization and a decreasing rural population in China. Figure 1 presents the penetration of room ACs in China in the BAU scenario at the national, urban and rural levels along with a comparison between the results based on this study our estimates and those of other studies. The projections based on this study are very close to O'Gresady and Narsipur (2018) [60], Kalanki (2019) [61] and IEA (2018) [2] in 2030, whereas in 2050 the deviation with IEA (2018) [2] is larger primarily due to the difference in the macro-economic assumptions. Detailed results on the penetration of residential ACs at the provincial level for China are presented in Table S5 of the SI.

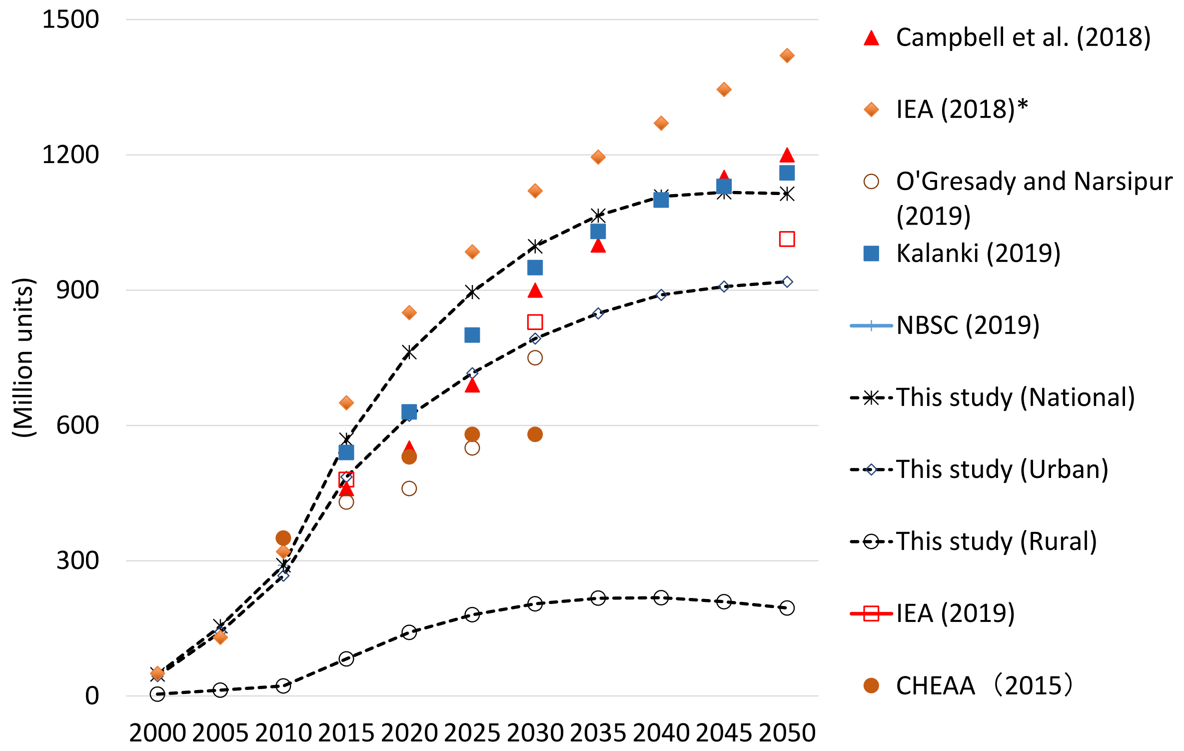

Figure 1. Comparison of room ACs stock under reference scenario with other studies
*IEA (2018) [2] data extracted from Geman (2018) [64].

3.2 Electricity consumption under BAU and alternative scenarios

Figure 2 presents the technical and economic electricity savings potential when moving from the BAU to alternative scenarios. As mentioned above, in the alternative scenarios we have taken into account a) the technical/economic energy efficiency potential of room ACs, and b) technical/economic efficiency improvement due to transition towards low-GWP alternatives (i.e. HC-290) instead of high-GWP HFCs (i.e. HFC-410A/HFC-32). The technical losses in the transmission and distribution (T&D) of electricity have been taken into account [65], whereas non-technical losses (NTL) have not been included in estimating the electricity saving potential. With reference to Lin et al. (2018) [66], we set the technical losses at 5%, which means there is a 5% difference between the generated capacity in power plants and distributed capacity. The electricity consumption in the BAU scenario for space cooling in the Chinese residential building sector is expected to reach 1314 TWh in 2050 as compared to 503 TWh in 2015 and 961 TWh in 2030. The energy consumption trends reflect the huge growth potential for space cooling in the Chinese residential building sector and are similar to the projected energy consumption growth for China in IEA (2010) [68]. In addition, the results of the four alternative scenarios analyzed in this study indicate a significant electricity saving potential through the adoption of energy-efficient ACs and transition towards low-GWP refrigerants (see Table S9). The electricity consumption in 2050 is estimated at 368 TWh in the EAC(T)+KA scenario (efficient AC along with low-GWP refrigerants (i.e. HC-290) using technical energy efficiency potential), indicating an electricity saving potential of 996 TWh, equivalent to about 4% of total Chinese building energy consumption in 2050 [69].

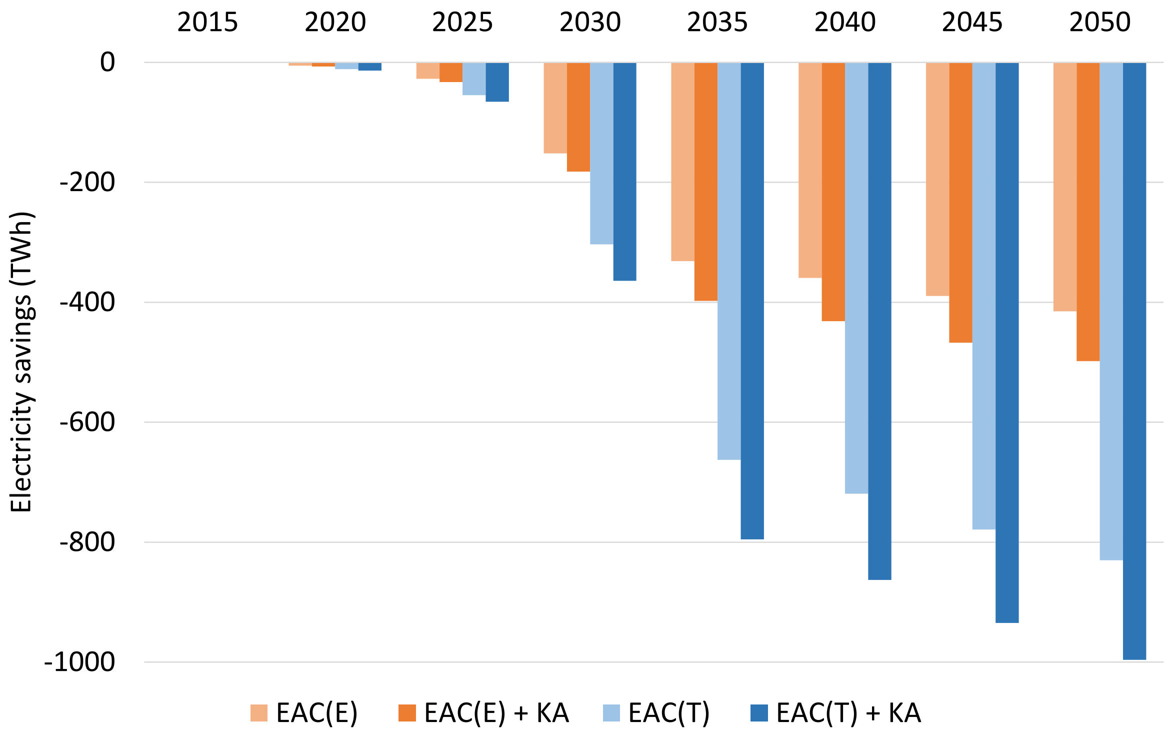

Figure 2. Electricity savings in the alternative scenarios as compared to the BAU scenario

The results presented in Table S9 exhibit the annual technical electricity saving potential in the alternative scenarios relative to the BAU by the province in China. The technical electricity saving potential under the KA is estimated at 364 TWh in 2030 and is limited by assumptions about inertia in technology uptake. By 2050, no inertia in technology uptake apply and the technical electricity saving potential is 996 TWh when also considering a transition to low-GWP refrigerants under the KA. This is equivalent to avoiding 284 new coal-fired power plants of 500 MW each assuming a capacity factor of 80%.

3.3 GHG mitigation due to HFC phase-down with enhanced energy efficiency

The electricity-savings presented in Figure 2 and Table S9 can be converted to approximate reductions in CO_2 emissions from electricity generation if we combine them with implied emission factors for CO_2 that reflect the expected specific fuel mixes used in the power plant sector of China in the IEA's World Energy Outlook 2018 current policies, new policies and sustainable development scenarios, respectively. Such implied emission factors are available from IIASA's GAINS model in the timeframe to 2050 [70]. In addition, apart from direct savings in CO_2 emissions from fuel combustion in power plants, there will also be savings in methane (CH_4) emissions in the upstream fossil fuel production sector. Noted that CH_4 emissions from coal mining in China have risen despite stricter government regulations that aimed to curb the greenhouse gas emissions[87]. The implied emission factor in kt CH_4 per Mt coal produced from Chinese coal mines and the corresponding implied emission factors per PJ oil and gas produced, were taken from IIASA's GAINS model. Estimated CH_4 emissions per TWh electricity saved take account of expected changes over time in the fuel mix of electricity production as represented in the different IEA-WEO 2018 scenarios. Except for special illustration, the emission factors used in emissions analysis in this article are taken from the new policies scenario (NPS) of the IEA's World Energy Outlook 2018.

In the BAU scenario, HFC emissions associated with room ACs increased from 115 Mt CO_2eq in 2015 to 125 Mt CO_2eq in 2030 and 133 Mt CO_2eq in 2050 (see Section S4), whereas CO_2 emissions due to electricity consumption reach 359 Mt in 2050 as compared to 164 Mt in 2015 and 292 Mt in 2030. In addition, the upstream CH_4 emissions associated with the electricity consumption are estimated at 32 Mt CO_2eq in 2050 as compared to 27 Mt CO_2eq in 2015 and 37 Mt CO_2eq in 2030. Hence, total CO_2eq emissions associated with energy consumption and refrigerant use increase from 306 Mt CO_2eq in 2015 to 454 Mt CO_2eq in 2030 and 524 Mt CO_2eq in 2050 using the implied emission factor from the IEA-WEO 2018 NPS scenario. Figure 3 presents the results of GHG mitigation from the Chinese residential building sector under the alternative scenarios in 2030 and 2050, respectively, as compared to the BAU scenario.

In 2050, under EAC(T)+KA scenario, CO_2 mitigation from electricity savings is estimated at 272 Mt using NPS variants, whereas GHG mitigation due to transitioning towards low-GWP refrigerants reaches 122 Mt CO_2eq, and the GHG reduction from the upstream CH_4 emissions due to electricity savings is estimated at 25 Mt CO_2eq. Therefore, the total GHG mitigation potential for the Chinese residential building sector when accounting for both the electricity savings and the transition to low-GWP refrigerants is estimated at 420 Mt CO_2eq in 2050. This is equivalent to approximately 10% of the total building sector CO_2 emissions and nearly 3% of the total CO_2 emissions in China in 2050 [69, 71, 72].

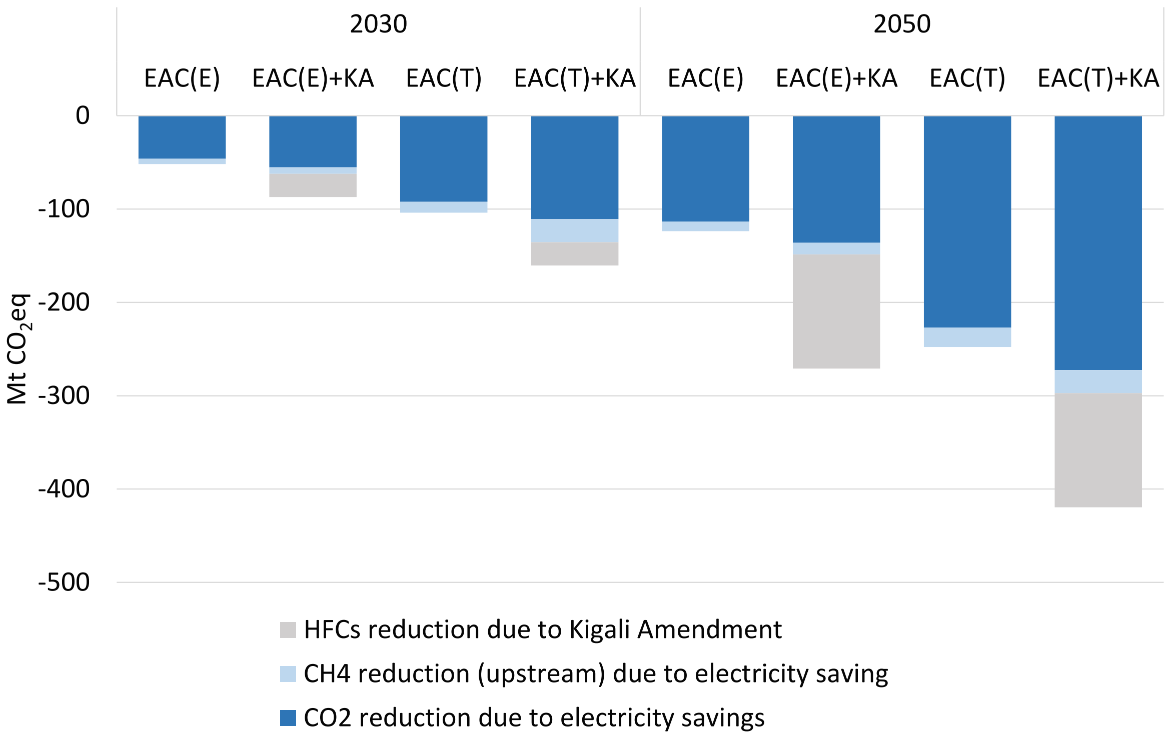

Figure 3. GHG mitigation in the alternative scenarios

Figure 4 presents CO_2 mitigation in the alternative scenarios due to electricity savings induced by the HFC phase-down and under assumptions of technical and economic energy efficiency improvements, respectively, as well as implied emission factors from the CPS, NPS and SDS variants, respectively. Relative to the BAU scenario, the CO_2 mitigation potentials under the KA scenario and assuming a technical energy efficiency improvement potential are estimated at 117 Mt CO_2eq in 2030 and 402 Mt CO_2eq in 2050 using implied emission factors from the IEA-WEO 2018 CPS scenario. The CO_2 mitigation potentials due to transitioning towards low-GWP HFC alternatives for meeting the KA targets under the assumption of economic energy efficiency improvements are more limited at 58 Mt CO_2 and 201 Mt CO_2, respectively, in 2030 and 2050, using CPS variants. As expected, reductions in CO_2 emissions using the NPS and SDS variants are lower as compared to the CPS in all scenarios presented in Figure 4, primarily due to higher penetration of clean fuels (gas, renewables etc.) and energy efficiency measures in the power sector. The range is a reflection of the different degrees of decarbonization of the energy system inherent in the CPS, NPS, and SDS as specified in the IEA-WEO 2018. In the CPS, the future electricity supply relies more heavily on fossil fuels and less on renewables than in the SDS, promoting CO_2 mitigation from electricity saving to be larger in the current policies scenario. The electricity-savings can be reaped when the air-conditioning equipment that uses alternative technologies to HFCs are properly installed and maintained, as the CO_2 reductions of these electricity-savings correspond to a significant fraction of total GHG emission reductions from high-GWP HFC (e.g. HFC-410A) phase-down. GHG mitigation at the provincial level due to the enhanced energy efficiency of room ACs using low-GWP refrigerants and substitution of high-GWP refrigerants is presented in Figure S7 of the SI. It is observed that GHG mitigation from refrigerant emissions together with the CO_2 mitigation from electricity-savings varies significantly across provinces. Most provinces with large GHG mitigation potential are concentrated in Hot Summer and Warm Winter or Hot Summer and Cold Winter climate zones, such as Guangdong, Jiangsu, Zhejiang, and Hubei provinces due to the higher temperature and longer duration of summer than other provinces (Table S9). This kind of climate zone division is consistent with the Chinese architectural climate zone planning map in the Code for Design of Civil Buildings (GB50352-2005)[75].

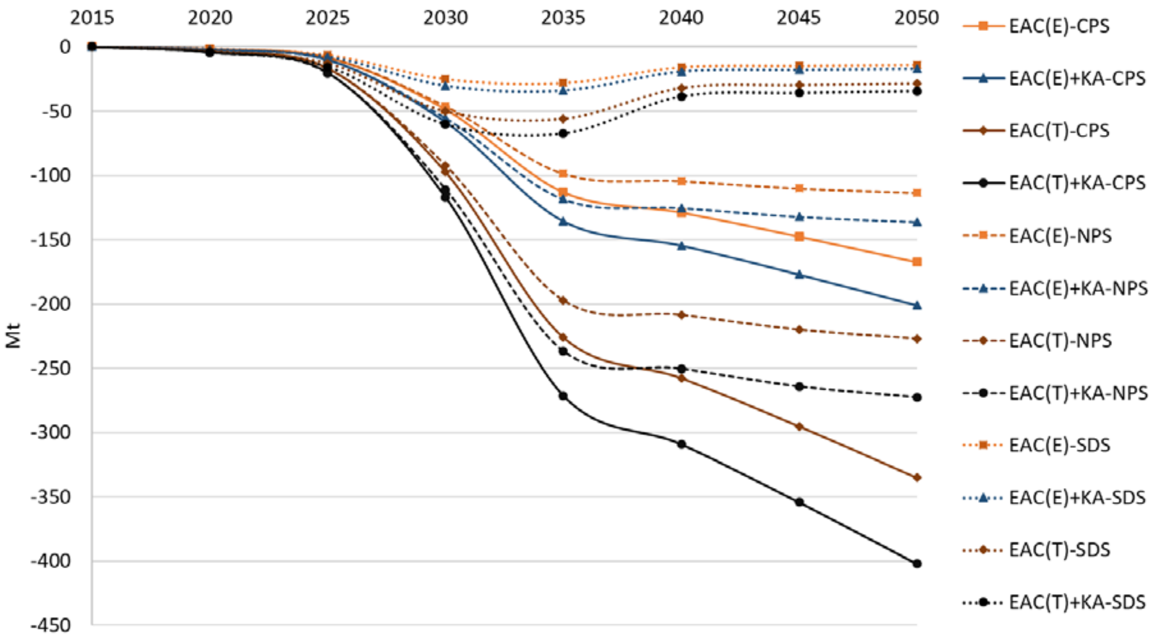

Figure 4. Annual CO_2 mitigation in alternative scenarios relative to the BAU scenario due to electricity savings

3.4 Air pollutant and SLCP emissions due to HFC phase-down with enhanced energy efficiency

Another major environmental benefit of reduced electricity demand for cooling technologies is improved air quality and fewer related adverse health and ecosystem effects [73, 74]. The electricity generation units that respond to this increased demand are major contributors to SO_2 and NO_x, both of which have direct impacts on public health, and contribute to the formation of secondary pollutants including ozone and $PM_{2.5}$. In 2015, residential space cooling was responsible for 9% of global SO_2 emissions from the power sector and 8% of NO_x and $PM_{2.5}$ emissions from the power sector [2].

Figure 5 presents the reductions in air pollutants and SLCPs emissions in alternative scenarios due to the HFC phase-down with associated improvements in the technical and economic energy efficiency potential of room ACs relative to the BAU scenario. According to the projection of this study, in 2050, the air pollutants reduction potential in EAC(T)+KA scenario is estimated at 133 kt SO_2, 227 kt NO_x, 39 kt $PM_{2.5}$ using the implied emission factors obtained from IEA-WEO 2018 CPS scenario as shown in Figure 5 (a-c). Figure 5 (d-e) indicates the annual reductions of SLCPs, including BC, and OC, in the alternative scenarios due to electricity-savings associated with HFC phase-down when assuming technical and economic energy efficiency improvements in cooling technologies. In 2050, the SLCPs reduction potential in EAC(T)+KA scenario is 0.6 kt BC, 2.8 kt OC with CPS variants.

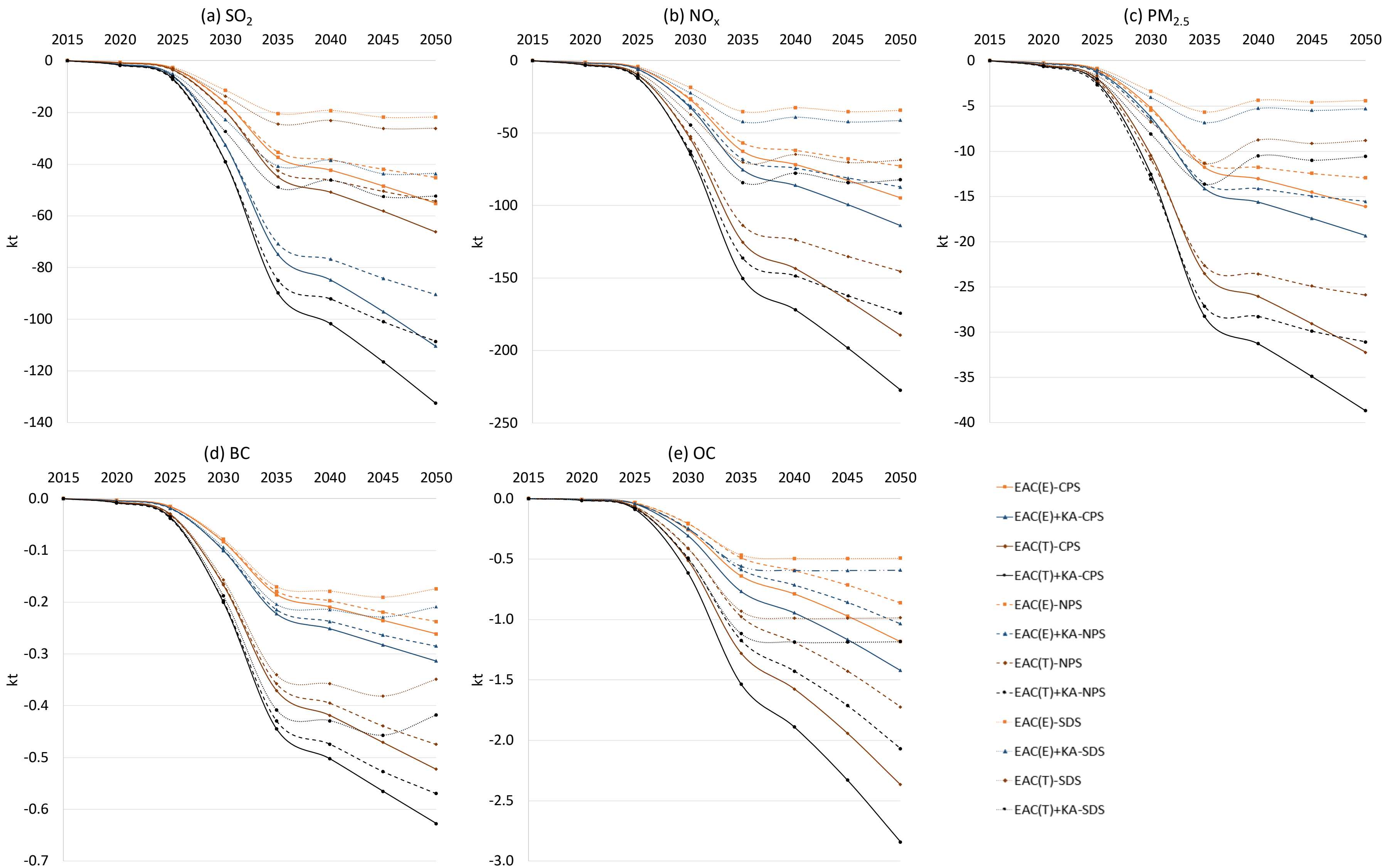

Figure 5. Annual air pollutants and SLCPs emission reductions in the alternative scenarios relative to the BAU scenario

3.5 Policy implications and future directions of research

In the last two decades, China had the fastest growth in space cooling energy consumption worldwide, driven by increasing income and growing demand for thermal comfort. In this study, we model future penetration of room air-conditioners (ACs) in the residential building sector of China at the provincial level, with consideration of urban-rural heterogeneities. Using market data and considering factors such as expected changes in climatic conditions and income, we first develop a business-as-usual (BAU) scenario for the future penetration of room ACs by 2050 in China. We then estimate the associated impacts on electricity demand considering the scopes for technical and economic energy efficiency improvements in room ACs and the energy efficiency benefits associated with the transition to low-GWP refrigerants.

The results indicate that increasing income, growing demand for thermal comfort and warmer climate conditions, are expected to drive an increase in the stock of room ACs in China from 568 million units in 2015 to 997 million units in 2030 and 1.1 billion units in 2050. In urban China, room AC ownership per 100 households is expected to increase from 114 units in 2015 to 219 units in 2030 and 225 units in 2050, with slow growth after 2040 due to the saturation of room ACs in the urban households of China. Ownership of room ACs per 100 households in rural China increases from 48 units in 2015 to 147 units in 2030 and 208 units in 2050. The total number of room ACs in rural China increases from 82 to 218 million units between 2015 and 2040 and then decreases slightly to 208 million units by 2050 primarily due to rapid urbanization and decreasing rural population.

There exists a large energy efficiency improvement potential in the room AC sector in China. Therefore, strong efficiency improvement policies can make a significant dent in the energy consumption of space cooling in the Chinese residential building sector. Currently, the AC efficiency improvement does not keep up with the growth rate of AC penetration. The average energy efficiency of ACs sold in the market is only 40% of the best available efficiency level and 80% of the market average available efficiency [8]. Without strong policy incentives to improve the energy efficiency of ACs, the energy consumption will expand to 1314 TWh in 2050 as compared to 961 TWh in 2030 and 503 TWh in 2015. The alternative scenarios analyzed in this study indicate a remarkable electricity saving potential through the enhanced energy efficiency of room ACs using low-GWP refrigerants (i.e. HFC-290). The electricity consumption in 2050 is estimated at 368 TWh using a technical energy efficiency potential, indicating an annual electricity saving potential of 996 TWh, which is equivalent to about 4% of expected total building energy consumption in 2050 [69].

Phasing down the use of high-GWP refrigerants provides a great opportunity for policymakers to move to a low-carbon society in China. Our results indicate that the BAU emissions of HFCs from the room AC sector are expected to increase from 115 to 125 Mt CO_2eq between 2015 and 2030 and reaching 133 Mt CO_2eq in 2050, prior to the commitments made by China under the Kigali Amendment (KA) to the Montreal Protocol. The growth is mainly driven by increasing penetration of room ACs in urban and rural households, which in turn is driven by an expected increase in per capita wealth in China, a warmer future climate, combined with the effect of replacing HCFCs with HFCs in accordance with the 2007 revision of the Montreal Protocol. Transitioning to low-GWP refrigerants in room ACs in compliance with the KA, the residential building sector of China is expected to reduce HFC emissions by 20% in 2030 and 92% in 2050 as compared to the BAU scenario.

The potential for improved energy efficiency due to the adoption of low-GWP refrigerants (HC-290) and energy efficiency improvements of the AC systems (i.e. efficient compressors, heat exchangers, etc.) can significantly reduce electricity consumption from room ACs in the residential building sector. The cumulative CO_2 mitigation due to these energy efficiency improvements makes up 2.6% of total CO_2 emissions expected to be emitted in China over the period 2020 to 2050.

China can deliver significant energy savings and associated reductions in GHG and air pollution emissions in the building sector by developing and implementing a comprehensive national policy framework, including legislation and regulation, information programs and incentives for industry. Energy efficiency and refrigerant standards for room AC installations should be an integral part of such a framework. Training and awareness raising can also ensure proper installation, operation and maintenance of air conditioning equipment and systems, and mandatory good practice with leakage control of the refrigerant during the use and end-of-life recovery. Improved data collection, research and co-operation with manufacturers can equally help to identify emerging trends, technology needs and energy efficiency opportunities that enable sustainable cooling. Although this article systematically analyzes the co-benefits of space cooling in the Chinese residential building sector, the model can be extended in the future to also consider consumer behavior influence and future trends in the air-conditioning industry.

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Supporting Information

Additional information for methods; Additional data and results at the provincial level with rural and urban disparity, Additional description of different refrigerants used in ACs along with baseline and HFC phase-down schedule of Article 5 countries of the Montreal Protocol;

Additional results on air pollutants, SLCPs, as well as GHG mitigation at the provincial level due to enhanced ACs system efficiency and the substitution of high-GWP refrigerants.

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