

Transitioning to low-GWP alternatives with enhanced energy efficiency in cooling non-residential buildings of China

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Abstract:

The electricity demand for space cooling in the non-residential building (NRB) sector of China is growing significantly and is becoming increasingly critical with rapid economic development and mounting impacts of climate change. The growing demand for space cooling will increase global warming due to emissions of hydrofluorocarbons used in cooling equipment and carbon dioxide emissions from the mostly fossil fuel-based electricity currently powering space cooling. This study uses the Greenhouse Gas - Air Pollution Interaction and Synergies (GAINS) model framework to estimate current and future emissions of hydrofluorocarbons and their abatement potentials for space cooling in the NRB sector of China and assess the co-benefits in the form of savings in electricity and associated reductions in greenhouse gas (GHG), air pollution and short-lived climate pollutant emissions. Co-benefits of space cooling are assessed by taking into account a) regional and urban/rural heterogeneities and climatic zones among different provinces; b) technical/economic energy efficiency improvements of the cooling technologies; and c) transition towards lower global warming potential (GWP) refrigerants under the Kigali Amendment. Under the business-as-usual (BAU) scenario, the total energy consumption for space cooling in the NRB sector will increase from 166 TWh in 2015 to 564 TWh in 2050, primarily due to the rapid increase in the floor space area of non-residential buildings. The total GHG mitigation potential due to the transition towards low-GWP refrigerants and technical energy efficiency improvement of cooling technologies will approximately be equal to 10% of the total carbon emissions from the building sector of China in 2050.

Key words: Hydrofluorocarbons, Low-GWP alternatives, Energy efficiency, Commercial air-conditioning, Kigali amendment, Co-benefits

1. Introduction

The global energy consumption of space cooling in the building sector is growing faster than other sectors and has more than tripled between 1990 and 2016 (IEA, 2018a). Space cooling is expected to account for an ever-increasing share of energy use with particularly strong growth in emerging economies. According to the recent IPCC (Intergovernmental Panel on Climate Change, IPCC) special report on global warming of 1.5 °C (IPCC, 2018), rapid and deep reductions in greenhouse gas (GHG) emissions from the cooling sector will be required to limit warming to 1.5°C (UNEP, 2021). The People’s Republic of China had the fastest growth in space cooling energy consumption worldwide in the last two decades (IEA, 2019), driven by increasing income and growing demand for thermal comfort. Cooling energy consumption in the non-residential building (NRB) sector represented about half of total cooling energy consumption in 2017 and increased nearly fivefold since 2000, compared with threefold floor area growth during the period (IEA, 2019). This reflects an increasing intensification of cooling energy demand, where the average cooling intensity increased from 10 kWh/m² in 2000 to 15 kWh/m² in 2017 (IEA, 2019). One factor in this growth is the design of heating, ventilation, and air conditioning (HVAC) systems that require “full time” and “full space” operations, particularly as building design for NRBs has moved increasingly to central HVAC systems using full-time mechanical ventilation. Among other types, cooling energy consumption of data centers has also grown rapidly in recent years (Jones, 2018; van Erp et al., 2020), due to rapid growth in scale and much higher cooling intensities than conventional NRBs.

Cooling in NRBs (commercial air conditioning) presents a key opportunity for reducing GHG emissions by cutting down fossil fuel-based electricity consumption through improved efficiency (Engelmann et al., 2014; Khanna et al., 2019; Purohit et al., 2020) and by transitioning to low-GWP (Global Warming Potential, GWP) refrigerants (Sharma et al., 2014; Höglund-Isaksson et al., 2017; Purohit et al., 2018; Wang et al., 2020). The Kigali Amendment (KA)¹ to the Montreal Protocol on Substances that Deplete the Ozone Layer (entered into force on 1 January 2019) is an international agreement to gradually reduce the consumption and production of hydrofluorocarbons (HFCs). It is a legally binding agreement designed to create rights and obligations in international law. Under the KA, 197 countries committed to reduce the production and consumption of hydrofluorocarbons (HFCs) — potent greenhouse gases mostly used in refrigeration and air conditioning — by more than 80% over the next 30 years. While previous agreements have resulted in improvements in the design and energy performance of, for instance, cooling equipment, the KA is the first to include maintaining and/or enhancing the energy efficiency of cooling technologies as an explicit goal (Purohit et al., 2022). If the Parties to the Montreal Protocol are able to strike a deal that enables the rapid introduction of highly energy-efficient appliances alongside a phase-down of high Global Warming Potential (GWP) HFCs, the total reduction of GHG emissions could be more than doubled (WMO, 2018b).

In this study, we have used the GAINS (Greenhouse Gas and Air Pollution Interactions and Synergies) model framework (Amann et al., 2020) to assess current and future HFC emissions and their abatement potentials for space cooling in the NRB sector of China and assess the co-benefits in the form of savings in electricity and associated reductions in GHG, air pollution and short-lived climate pollutant (SLCP) emissions. The rest of this paper is structured as follows: Section 2 briefly presents an overview of energy consumption and energy efficiency of space cooling technologies in the NRB sector of China. Section 3 shows the methodology used to assess the co-benefits of HFC phase-down with enhanced energy efficiency in the NRB sector of China. Section 4 illustrates the results and conclusions are drawn in Section 5.

2. Overview of the Chinese non-residential building sector

2.1 Overview of the scale development

To achieve sustainable economic growth, the Chinese government and associated administrative entities have strived to stimulate a series of enactments and regulations focusing on the building energy conversation, which have explicitly pointed out the importance of energy conservation in public and NRB sectors. In 2007, the Chinese

¹ 136 signatories have ratified the Kigali Amendment to the Montreal Protocol on phasing down HFCs worldwide, as of June 2022 (UN, 2022). China, a major producer of these chemicals, ratified the amendment effective September 15, 2021.

Ministry of Housing and Urban-Rural Development (MOHURD) and the Ministry of Finance (MOF) jointly issued the regulations for the energy conservation, supervision of state offices and large public buildings, which have clearly stipulated the energy consumption surveys, statistics management, and audits related to public and NRB sectors (MOHURD and MOF, 2007). Hereafter, the statistics management and audits on the energy consumption of different types of public buildings and various end-uses have been carried out throughout the country. At present, some advanced cities in China have begun to publish energy consumption information of public and NRBs on a regular basis (THUBERC, 2018), such as Shanghai and Shenzhen. In addition, some other cities have conducted several surveys on the energy consumption of public buildings, which also provides valuable basic data for this research.

Due to the rapid urbanization, sustained development of the building sector has led to a huge increase in the construction area in China, and it is still growing. The total building floor space in China has increased from 37.3 billion m² to 60.9 billion m² in the past two decades or so, of which urban residential building floor space is about 24.7 billion m², rural residential building floor space is around 23.2 billion m², and NRB floor space is about 12.9 billion m² (THUBERC, 2020; Han, 2021). In 2019, the floor space per capita of rural residential buildings, urban residential buildings and NRB were 48.9 m², 39.8 m² and 9.2 m² respectively. The detailed changes of various building types are shown in Figure 1. The floor space of the NRB sector has more than tripled, increasing from about 4 billion m² in 2001 to around 13 billion m² in 2019 (Figure 1), and has the fastest growing speed among all building sub-sectors, with an average annual growth rate of 11% in the past two decades or so.

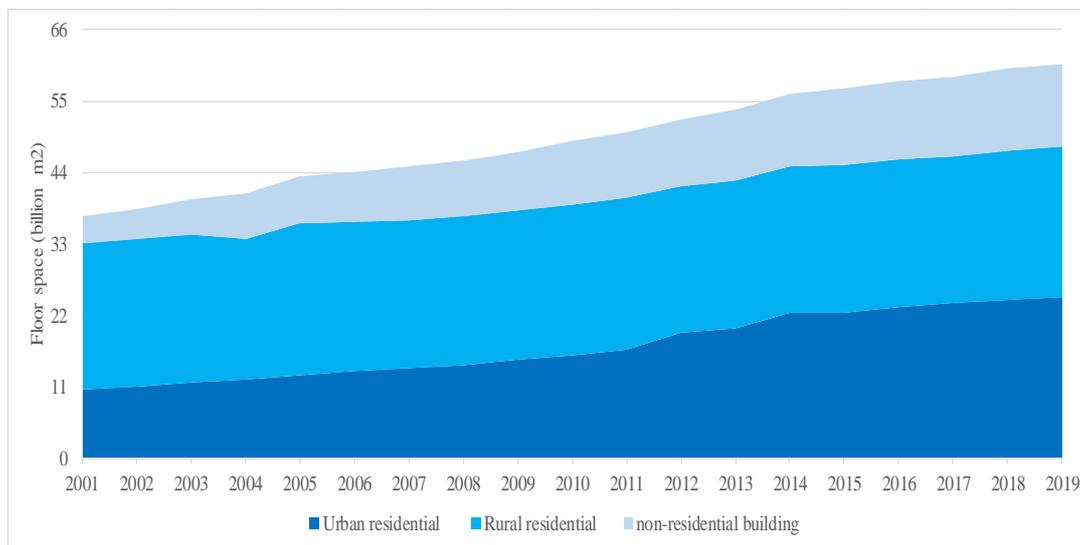


Figure 1. The change in various types of building areas from 2001 to 2019

Source: (THUBERC, 2020; MOF, 2021)

Despite the continuous growth of building floor space in China, there is still a great growth potential compared with the industrialized countries. Figure S1 presents the average building floor space per capita in China and other countries whereas the average building floor space per capita of NRB types in China and other industrialized countries is presented in Figure S2 of the Supplement Information. In addition, with the continuous development of the economy and society, the increase in demand for the quality of life will bring about the rapid growth of the total floor space of Chinese NRB, especially the demand for public social services buildings, including hospitals and schools. However, with the consideration of rapid e-commerce development in China, it is difficult to maintain sustained growth in retail buildings, so hospital buildings, as well as school buildings, will become the main drivers of growth in the next stage. Especially, when refined to different NRB types, with the development of knowledge-intensive industries such as information and finance, the number of people working in office buildings will increase. On the other hand, the high vacancy rate of office buildings makes the government put forward stricter requirements on the construction of new office buildings (Savills, 2019; THUBERC, 2018), together with the spread of the COVID-19 pandemic has changed the way humans work (IEA, 2021), so it is expected that there will only a small increase in office buildings.

Table 1 presents the description of the current and 2035 forecasts of different types of NRBs (THUBERC, 2018). From 2016 to 2035, it is assumed that the proportion of various buildings will maintain a constant growth or decline. There is no data on the scale development plan of public buildings from 2035 to 2050 and considering that the urbanization level of China will be at a relatively high level in 2035, the proportion of various NRBs has been able to meet the living needs of people. The future development will be more of an increase in the total building scale, while the proportion of different types of NRBs is basically unchanged. Therefore, it is assumed in this study that from 2035 to 2050, the scale of different NRB types will remain unchanged at the 2035 level.

Table 1. The description of the current and 2035 forecasts of different types of non-residential buildings

Types	2016		2035	
	Proportion of scale	Floor space per capita (m ²)	Proportion of scale	Floor space per capita (m ²)
Office	37%	3.1	28%	3.4
Retail	4%	0.4	5%	0.6
Hospital	18%	1.6	17%	2.1
School	14%	1.2	20%	2.4
Hotel	4%	0.3	7%	0.8
Others	23%	1.9	24%	2.8
Total	100%	8.5	100%	12.2

Source: THUBERC, 2018.

2.2 Energy consumption and carbon dioxide emissions

The floor space of NRB only accounts for one-fifth of the total floor space of the Chinese building sector as shown in Figure 1 above, however, the total energy consumption of NRB is higher than rural/urban residential buildings due to the high energy use intensity of NRB sector. The whole life-cycle energy consumption of the building sector includes the energy consumption of the construction material production, building construction, and building operation stages. In 2018, the whole life-cycle energy consumption of the Chinese building sector was approximately 2.147 billion tce (ton of standard coal equivalent), accounting for 46.5% of Chinese total energy consumption (CABEE, 2020). The energy consumption of building operations is about one billion tce, accounting for 46.6% of the whole life-cycle energy consumption of the building sector and about 21.7% of the total energy consumption of China in 2018. Among the building operation energy consumption of all building types, the energy consumption of NRB was around 0.383 billion tce, accounting for 38.3% of all building types, and the energy use intensity per m² was about 29.73 kgce (kilogram of standard coal equivalent); as for urban residential building sector, the energy consumption was about 0.38 billion tce, together with the energy use intensity as 12.38 kgce/m² referring to the rural residential building sector, the total energy consumption was about 0.237 billion tce, and the energy use intensity was about 9.98 kgce/m² (CABEE, 2020). The detailed energy consumption of different building types is shown in Figure 2.

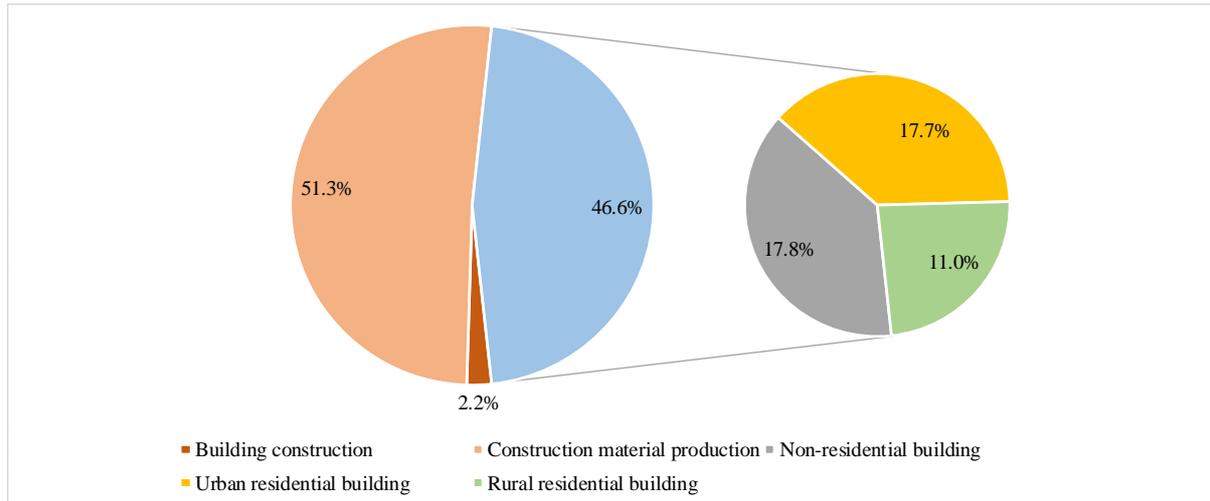


Figure 2. The detailed energy consumption of different stages and different building types

Source: CABEE (2020).

In 2018, the carbon dioxide (CO₂) emissions of the Chinese building sector were approximately 2.11 Gt, accounting for nearly 21.9% of the total national CO₂ emissions (CABEE, 2020). Among them, the total CO₂ emissions of the NRBs sector was about 784 Million ton (Mt), accounting for 37.1% of the whole CO₂ emissions from the building sector, with a CO₂ emission intensity of 60.78 kg/m² (CABEE,2020). The total CO₂ emissions of urban residential buildings were 891 Mt, accounting for 42.2% of the total CO₂ emissions from the building sector with a CO₂ emission intensity of 29.02 kg/m². Similarly, the total CO₂ emissions of rural buildings were 437 Mt, accounting for 20.7% of the total CO₂ emissions from the building sector, together with a CO₂ emission intensity of 18.36 kg/m² (CABEE, 2020). It is observed that the CO₂ emission intensity of NRBs is about 2-3 times that of urban and rural residential buildings. While the total floor space of NRBs is growing rapidly, the proportion of large-scale NRBs has also increased significantly. Due to the volume and structure constraints of the large-scale NRBs, the energy use intensity of air conditioning, ventilation, lighting, and elevators is much higher than that of ordinary buildings, which is the most important reason for the continuous increase in energy use intensity of NRB.

In terms of the trends of energy consumption and CO₂ emissions of the Chinese building sector (Figure 3), the whole life-cycle energy consumption has increased from 0.93 billion tce in 2005 to 2.15 billion tce in 2018 (THUBERC, 2019; THUBERC, 2020), an increase of 2.3 times with an average annual growth rate as 6.6%. The changes in the whole life-cycle energy consumption of the building sector show significant characteristics in different phases: during the period from 2005 to 2010, the Eleventh Five-Year Plan (FYP), the energy consumption of the building sector showed a steady growth trend and the growth rate is relatively stable, however, during the Twelfth FYP (2011 to 2015), the energy consumption of the building sector increased sharply in 2011 and 2012, and then remained stable and declining in the next three years as shown in Figure 3(a). From 2016 to 2018 (that is the Thirteenth FYP already recorded), the energy consumption of the building sector continued to increase steadily while the growth rate has slowed down significantly. The dramatic growth in 2011 and 2012 is unreasonable, while the most possible reason is the statistical caliber of construction materials, rather than the fluctuations in the development of the construction industry itself. The associated CO₂ emissions are shown in Figure 3(b).

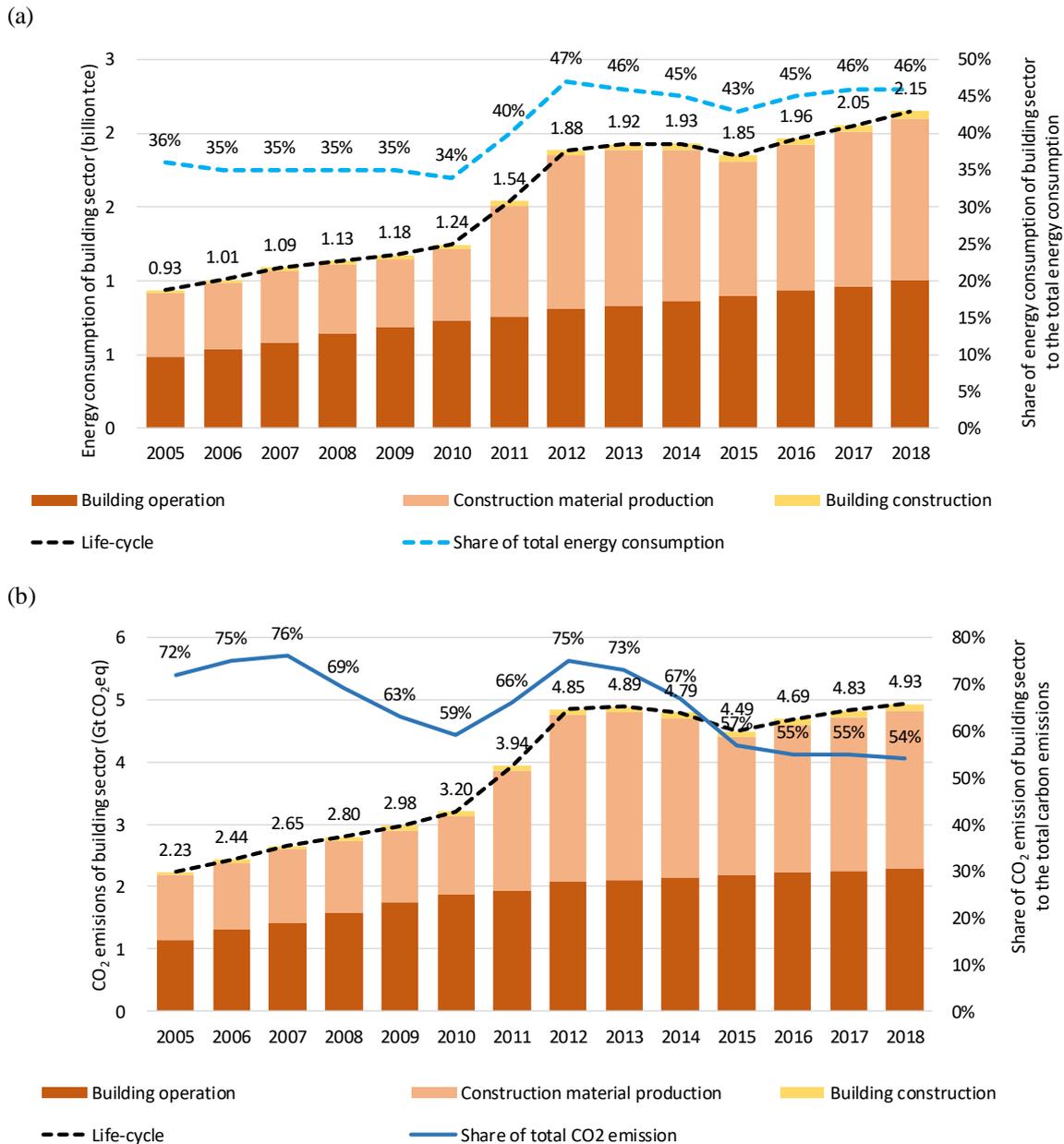


Figure 3. Trends in a) energy consumption and b) CO₂ emissions of the building sector in China

Source: (THUBERC, 2019; 2020).

The secondary axis of [Figure 3\(a\)](#) presents the energy consumption of the building sector as a share of the total energy consumption of all sectors in China whereas CO₂ emissions from the building sector as a share of the total CO₂ emissions from all sectors of the economy are presented in [Figure 3\(b\)](#). It is observed that the share of energy consumption of the building sector has increased from 36% in 2005 to 46% in 2018, whereas the share of CO₂ emissions of the building sector has dropped from 72% in 2005 to 54% in 2018. In terms of the volume, in 2018, the energy consumption of the building sector accounted for 46% of the total energy consumption, and the CO₂ emissions of the building sector accounted for 54% of the total CO₂ emissions in China, indicating that the average carbon emission factor of the building sector is higher than the average level of China. In terms of the changing trend, from 2005 to 2018, the proportion of energy consumption in the building sector continued to increase, while the share of CO₂ emissions has been decreasing for many years, demonstrating that the industry structure is continuously optimizing as well as the CO₂ emission factor is gradually declining.

2.3 Overview of the space cooling

According to the International Energy Agency (IEA), cooling energy demand in China reached just under 400 TWh in 2017 (IEA, 2019), roughly 8% of total electricity demand in the buildings sector. From 2000 to 2017, the average annual growth rate of the energy consumption of space cooling in the Chinese building sector reached 13% (IEA, 2019). Among all sub-types of the Chinese building sector, the energy consumption of space cooling in the NRB sector took up 28% of the total building energy consumption, and the office buildings together with the retail buildings are the largest proportion of consumption in the NRB sector (IEA,2019). Due to the rapid growth in the scale of the NRB sector and the growth in the proportion of large buildings, from 2000 to 2017, the total electricity consumption of space cooling in the NRB sector increased by around five times. According to the summary of a number of surveys and research data, in the overall energy consumption of NRBs, the energy consumption of air-conditioning (AC) and terminal equipment is the most important energy consumption sub-item, and the sum of the two accounts for around 90% of the total energy consumption in the NRB sector (THUBERC, 2008; 2009; 2014). Among them, the energy consumption of ACs accounts for about 38%-48% of the total consumption in the NRB sector as shown in Figure 4. The energy use intensity of different types of NRB also varies greatly, fluctuating between 30-300 kWh/m² annually and the gap between the maximum and minimum is dozens of times (Ma, 2015). The difference in energy consumption of different types of NRBs is mainly related to factors such as the function, running time, nature of use, energy service level, and energy management of the building (THUBERC, 2008).

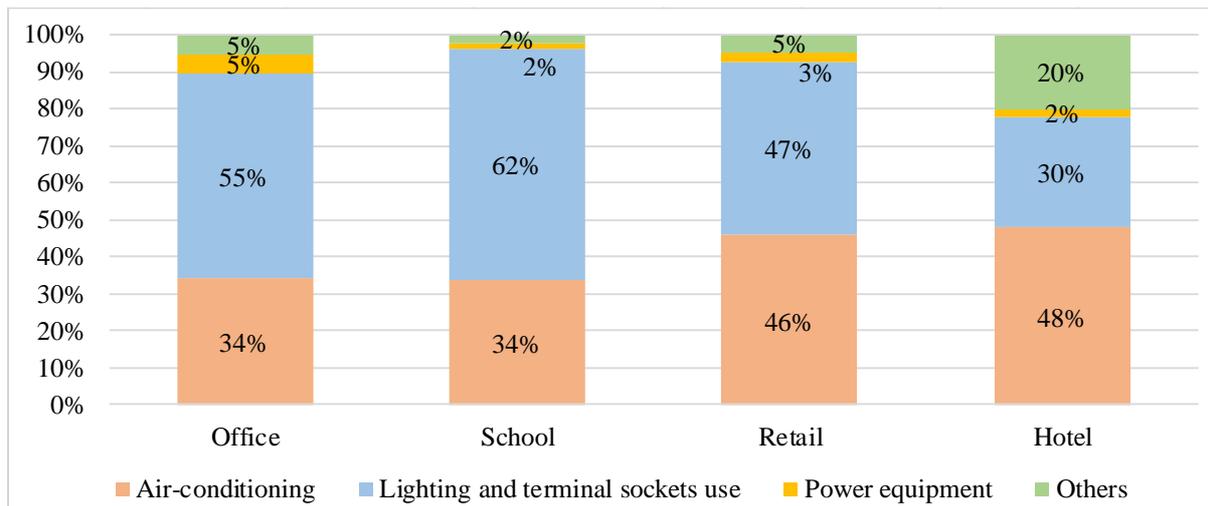


Figure 4. Composition of energy consumption of non-residential buildings

Source: (THUBERC, 2008; 2009; 2014).

In view of the huge potential of energy saving and greenhouse gases emission mitigation of space cooling in the NRB sector, China has issued a series of policies and regulations for space cooling equipment like the coefficient of performance (COP), summated refrigerating coefficient of performance (SCOP) of different equipment types in different regions. Table 2 presents details of energy efficiency regulations for ACs in the NRB sector. The warmer the climate, the higher the limit value of its energy efficiency standards, because of the reason that the energy efficiency of NRB air conditioning is highly affected by the local climate and environment. As a result, space cooling is the main energy consumption sub-sector of non-residential buildings, improving the energy efficiency of cooling technologies will have significant electricity savings and greenhouse gas mitigation potential in the NRB sector.

Table 2. The detail of energy efficiency regulations for air conditioning in non-residential building

Types		Cooling Capacity (kW)	Server cold climate region (SCR) A/B zone	Server cold climate region (SCR) C zone	Temperate climate region (TR)	Cold climate region (CR)	Hot summer and cold winter climate region (HSCWR)	Hot summer and warm winter climate region (HSWWR)	
			Coefficient of Performance (COP, W/W)						
Chiller (heat pump) unit	Water cooling	Piston /Scroll	CC≤528	4.10	4.10	4.10	4.10	4.20	4.40
			Screw	CC≤528	4.60	4.70	4.70	4.70	4.80
		528<CC≤1163		5.00	5.00	5.00	5.10	5.20	5.30
		CC>1163		5.20	5.30	5.40	5.50	5.60	5.60
		Centrifugal		CC≤1163	5.00	5.10	5.10	5.20	5.30
			1163<CC≤2110	5.30	5.40	5.40	5.50	5.60	5.70
	CC>2110		5.70	5.70	5.70	5.80	5.90	5.90	
	Air cooling/ Evaporative cooling	Piston /Scroll	CC≤50	2.60	2.60	2.60	2.60	2.70	2.80
			CC>50	2.80	2.80	2.80	2.80	2.90	2.90
		Screw	CC≤50	2.70	2.70	2.70	2.80	2.90	2.90
CC>50			2.90	2.90	2.90	3.00	3.00	3.00	
Types		Cooling Capacity (CC, kW)	Summated Refrigerating Coefficient of Performance (SCOP, W/W)						
Small DX /room AC unit	Water cooling	Piston /Scroll	CC≤528	3.3	3.3	3.3	3.3	3.4	3.6
			Screw	CC≤528	3.6	3.6	3.6	3.6	3.6
		528<CC≤1163		4	4	4	4	4.1	4.1
		CC>1163		4	4.1	4.2	4.4	4.4	4.4
		Centrifugal		CC≤1163	4	4	4	4.1	4.1
			1163<CC≤2110	4.1	4.2	4.2	4.4	4.4	4.5
CC>2110	4.5		4.5	4.5	4.5	4.6	4.6		

Notes: The (SCR) A/B/C zone is divided according to the requirements set out in [CNIS \(2015\)](#) and [CNIS \(2016\)](#) and is primarily determined on the basis of building design requirements for insulation, insulation, shade, and moisture protection of the certain area. The typical areas of the (SCR) A/B zone include Heihe, Qiqihar, Jiamus, Bilianhot, Manchuria, etc., and the typical areas of the (SCR) C zone include Changchun, Shenyang, Urumqi, Ordos, etc. For a detailed list of different climate zones and the building design requirements, please refer to [CNIS \(2015\)](#) and [CNIS \(2016\)](#).

Source: [CNIS \(2015\)](#).

3. Methodology and data sources

The conceptual framework of this study is shown in Figure 5. We estimate the total energy consumption of the NRB sector in China using commercial floor space and energy use intensity for space cooling in the commercial sector.

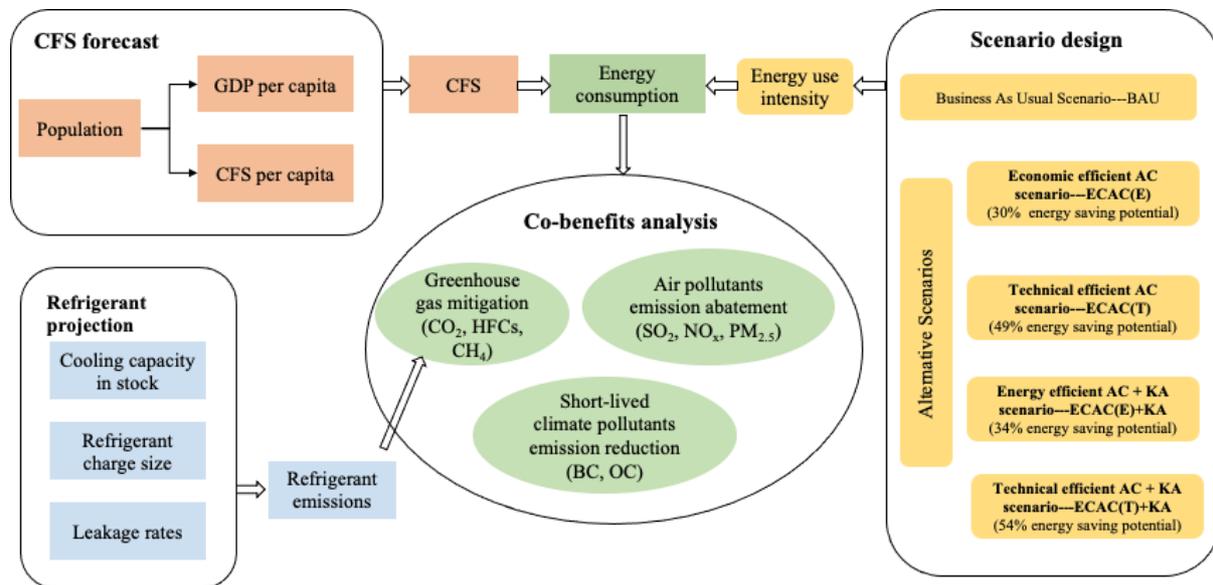


Figure 5. Conceptual framework of this study

3.1 Energy consumption for space cooling in non-residential buildings

The total energy consumption for cooling in NRBs is associated with the energy use intensity (EUI) and the total commercial floorspace (Gschrey and Schwarz, 2009; Ürge-Vorsatz et al., 2015). The data on commercial floor space area was correlated with GDP/capita (Purohit and Höglund-Isaksson, 2017) as illustrated in Figure 6. Fitting a linear trend line, the following relationship was retrieved:

$$\left[\left(\frac{\text{Commercial floor space}}{\text{Capita}} \right) = 0.0019 \left(\frac{\text{GDP}}{\text{Capita}} \right) + 1.8343 \right] \quad (R^2 = 0.58) \quad (1)$$

The historical data of the NRB sector at the provincial level is taken from THUBERC (2011) and THUBERC (2018). In order to eliminate the influence of extreme values on the regression coefficients, we selected the data of 21 provinces in Eq. (1). The forecast of commercial floor space is obtained from the projection of the population and GDP of each province until 2050 with a five-year interval. The population and GDP projections are consistent with UNDESA (2019) and the IEA's New Policies Scenario of the World Energy Outlook (WEO) 2018 (IEA, 2018b), respectively. The detailed provincial macroeconomic and demographic data as well as the provincial floor space data is presented in Table S1 and Table S2 of the Supplementary Information (SI).

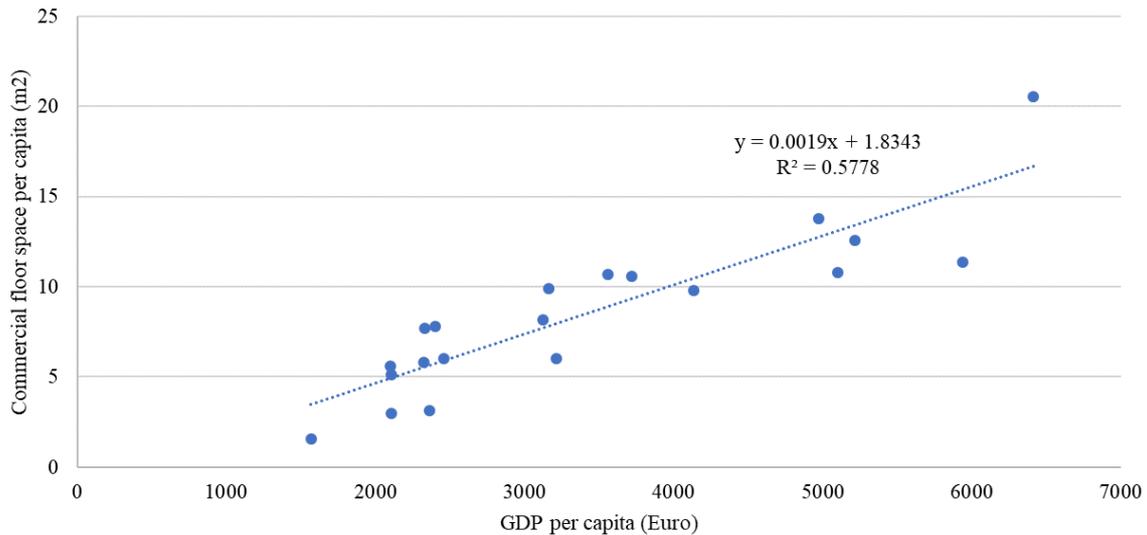


Figure 6. Variation of commercial floor space per capita with respect to the GDP per capita in the year 2015

Source: (IEA, 2018b; UNDESA, 2019)

The energy use intensity (EUI) represents the energy consumed per year for cooling per m² and is relevant to the income level and the climatic conditions of different regions. We have collected data on EUI for space cooling through publicly available literature and the annual report on energy monitoring and analysis for governmental offices and large-scale public and NRBs in several major cities (i.e., Qingdao in Shandong province, Wuhan in Hubei province, Ningbo in Zhejiang province, Dalian in Liaoning province, etc.) of China (SZJS, 2017; SZJS, 2018; THUBERC, 2018; SHJJW, 2019; THUBERC, 2014; Yang and Zhu, 2010; SHJJW, 2015; Lai et al., 2014; Song et al., 2011; Zhang et al., 2009). Owing to the differences in EUI in different climatic conditions, we correlate the city-level EUI information to the relevant climate zones in China. An average EUI of each climate zone is estimated if the data for more than one city is available in each climatic zone. In addition, depending on various types and applications of the building, we divide the public and NRBs into six categories, namely office, retail, hospital, school, hotel, and others. The EUI of different building types in China also varies significantly (Zhou et al., 2018;). Table 3 presents the EUI for space cooling of different climate zones and different building types considered in this study, and the detailed provincial data of EUI can be seen in Table S3 (see: SI). The final energy consumption for cooling in NRBs is estimated as a product of the energy use intensity and the total commercial floor space.

Nevertheless, most cities with public building energy monitoring systems in place have higher economic development as compared to other non-monitored cities. Using this data to represent the average level of each climate zone will lead to an overestimation of the results. So, in this study, after getting the EUI data of different NRB types for each climate zone, we adjusted them with reference to the average cooling intensity of 15 kWh/m²/year in 2015 (IEA, 2019). Eventually, the adjusted EUIs of different building types are adopted in this study as shown in the last column of Table 3. According to IEA (2019), the share of cooled floor space in the NRB sector of China was over 80% in 2015 which will increase to more than 95% in 2030. In this study, when we calculate the energy consumption in the NRB sector, we only consider the differences in commercial floor space and energy use intensity across the provinces, as the differences in economic level and climatic conditions are reflected in the energy use intensity.

Table 3. The energy use intensity (EUI) for different types of non-residential buildings in different climate zones

Climate zones	Building types	Provinces	Year	Energy use intensity (kWh/m ² /year)	EUI of space cooling accounts for total EUI (%) [*]	EUI for space cooling (kWh/m ² /year) [†]	Adjusted EUI for space cooling (kWh/m ² /year) [‡]
HSWWR	Office	Guangdong ^{a, b}	2016/2017	79/87.1	29.68%	27.98	16.07
	Retail	Guangdong ^{a, b}	2016/2017	177/209.2	29.30%	56.58	32.50
	Hospital	Guangdong ^a	2016	118.6	--	47.44	27.25
	School	Guangdong ^a	2016	73.1	--	21.93	12.60
	Hotel	Guangdong ^{a, c}	2015/2016	113/123	31.36%	37.00	21.25
	Others	Guangdong ^{a, c}	2015/2016	109/86	32.16%	31.36	18.01
HSCWR	Office	Shanghai ^{c, d}	2015/2016/ 2017/2018	77.25/88.15/ 89.85/87.75	33%	24.01	13.79
	Retail	Shanghai ^{c, d}	2015/2016/ 2017/2018	139.5/145.9/ 152.5/149.7	28%	45.03	25.87
		Hubei ^e	2014	200	--		
		Hunan ^f	2011	178	--		
	Hospital	Shanghai ^{c, d, g}	2013/2014/ 2015/2016/ 2017/2018	55.5/49.4/ 108.3/143.5/ 164.2/177.8	40%	43.24	24.84
		Hubei ^e	2014	78	--		
		Zhejiang ^e	2014	88	--		
	School	Shanghai ^g	2013/2014	72.9/48.6	--	17.15	9.85
		Hubei ^e	2014	50	--		
	Hotel	Shanghai ^{c, d, g}	2013/2014/ 2015/2016/ 2017/2018	124.3/105.9/ 120.7/124.8/ 130.5/126	30%	35.75	20.54
		Hubei ^e	2014	102	--		
	Others	Shanghai ^{c, d, g}	2013/2014/ 2015/2016/ 2017/2018	112.2/97.6/ 101/100.7/ 98.1/108	30%	30.88	17.74
TR	Office	Guizhou ^h	--	72.18 [‡]	--	21.70 [‡]	12.47
	Retail	Guizhou ^h	--				
	Hospital	Guizhou ^h	--				
	School	Guizhou ^h	--				
	Hotel	Guizhou ^h	--				
	Others	Guizhou ^h	--				
CR	Office	Tianjin ^e	2014	59	--	21.28	12.22

		Shaanxi ⁱ	2007/2008	65/50	--			
		Henan ^{j,±}	2017	--	--			
		Shandong ^c	2015	62	--			
	Retail	Tianjin ^e	2014	178	--		40.92	23.51
		Shanxi ^k	2011	96.2	--			
		Shandong ^c	2015	135	--			
	Hospital	Tianjin ^e	2014	107	--		31.40	18.04
		Shandong ^c	2015	50	--			
	School	Tianjin ^e	2014	50	--		15.00	8.62
	Hotel	Tianjin ^e	2014	100	--		30.00	17.23
		Shandong ^c	2015	100	--			
	Others	Shanxi ^k	2011	65	30%		25.40	14.59
		Beijing ^l	2012	104.31	--			
SCR	Office	Liaoning ^m	2009	59.67	19.07%	11.38	6.54	
	Retail	Liaoning ^m	2009	222.48	16.41%	36.51	20.97	
	Hospital	--	--	--	--	31.40 [§]	18.04	
	School	--	--	--	--	15.00 [§]	8.62	
	Hotel	Liaoning ^m	2009	112.98	13.98%	15.79	9.07	
	Others	--	--	--	--	21.23 [§]	12.20	

Notes: * When referring to “EUI for space cooling accounts for total EUI (%)”, not all the data for different regions are available. If this value is not available from the secondary literature, the default setting for “Office building” is 30%, the “Retail” is 30%, the “Hospital” is 40%, the “School” is 30%, the “Hotel” is 30%, and the “Others” is 30% (Ma, 2015; SHJW, 2019; SZJS, 2017; SZJS, 2018).

[†] This is calculated by authors taking the average of the data obtained from the literature survey.

[‡] The information about EUI in the “Temperate Climate Zone” is rare therefore we have used the average EUI for all types of NRBs in Guizhou Province.

[§] The EUI data of “Hospital” and “School” in “Serve Cold Climate Zone” is not available, therefore we just adopt the data from “Cold Climate Zone”.

[§] The EUI data for the “Others” type of NRB in the “Severe Cold Climate Zone” is not available and is calculated from the average of “Office building”, “Retail”, and “Hotel” NRBs.

ⁱ Most cities with public building energy monitoring systems have higher social and economic development as compared to other non-monitored cities. Using these data to represent the average level of each climate zone will lead to an overestimation of the results. Therefore, in this study, after getting the EUI data of different NRB types for each climate zone, we adjusted them with reference to the average cooling intensity of 15kWh/m²/year in 2015 (IEA, 2019).

[±]EUI for space cooling in Henan for Office buildings is 24.85 kWh/m² annually. Data is obtained from the “Application analysis platform of Public Building” available at http://www.qianjia.com/html/2017-06/02_270756.html (accessed 2nd October 2019).

Sources: a. SZJS (2017); b. SZJS (2018); c. THUBERC (2018); d. SHJJW (2019); e. THUBERC (2014); f. Yang & Zhu (2010); g. SHJJW (2015); h. Lai et al. (2014);

i. List of energy consumption of office buildings and public buildings in Shaanxi Province.

j. Application Analysis of Public Building Energy Monitoring Platform.; k. Song et al. (2011).

l. BMCHURD & BOBEEBMM (2013).

m. Zhang et al. (2009).

Table 4. The charge size and leakage rate of different types of cooling technologies used in the non-residential building sector

Commercial AC type	Capacity range	Refrigerant type ^a	Charge size (kg/kW) ^b	GWP ^c	Lifetime (years) ^d	Operational leakage (%) ^e	Servicing leakage (%) ^e	End-of-life leakage (%) ^e
Small DX or split room ACs	<5kW	HCFC-22/(R22)	0.167	1760	10	10%	10%	70%
		HFC-410A/(R410A)	0.140	1923.5				
		HFC-32/(R32)	0.100	677				
		HC-290/(R290)	0.083	1				
Medium-Large DX	5-100kW	HCFC-22/(R22)	0.310	1760	20	10%	10%	70%
		HFC-410A/(R410A)	0.260	1923.5				
		HFC-134a/(R134a)	0.365	1360				
		HFC-32/(R32)	0.186	677				
		CO ₂ /(R744)	0.183	1				
Chiller	100-2000kW	HCFC-22/(R22)	0.322	1760	20	10%	10%	70%
		HFC-134a/(R134a)	0.380	1360				
		HFC-32/(R32)	0.193	677				
		CO ₂ /(R744)	0.190	1				
		HFO1234ze(E)	0.418	1				
Others (like LiBr ACs, etc) ^f	--	Other fluorine-free refrigerants	--	--	--	--	--	--

Notes: a. The information about refrigerant types used in different cooling technologies in the commercial sector and their trends in the near future are compiled and analyzed by authors from relevant references, including [Sharma et al. \(2017\)](#), [Goetzler et al. \(2016\)](#), [Gschrey et al. \(2009\)](#) and [CRAA \(2014\)](#).

b. The charge size of different types of refrigerants used in different cooling technologies in the commercial sector are obtained from [Sharma et al. \(2017\)](#), [Ionescu \(2016\)](#), [Schwarz & Leisewitz \(1999\)](#) and [Li et al. \(2010\)](#).

c. The Global warming potential (GWP₁₀₀) of different refrigerant types refer to IPCC/AR5 ([IPCC, 2014](#)) and [WMO \(2018a\)](#). The GWP value of R290 is expressed as less than 1 as specified in [WMO \(2018a\)](#). In this study, we take GWP₁₀₀ = 1 for R290.

d. The lifetime of different types of commercial cooling technologies are obtained from [Sharma et al. \(2017\)](#).

e. The leakage rates in the operational process, servicing process and end-of-life are collected from [Sharma et al. \(2017\)](#) about the data in India and the [Expert group \(2010\)](#) about the data for Australia. After consulting with experts on commercial ACs in China, we decided to take the value between [Sharma et al. \(2017\)](#) and [Expert group \(2010\)](#) as 10% during operational process, 10% during servicing process, and 70% during the end-of-life period.

f. Others include all type of ACs not contained by the first three type of ACs, like Lithium Bromide (LiBr) ACs, which use the fluorine-free refrigerants and will not have any impact on the greenhouse gases in addition to the CO₂ emissions indirectly generated by electricity consumed during the operational period.

3.2 Refrigerant emissions from cooling in non-residential buildings

There are different types and sizes of cooling technologies used in the NRB sectors. According to different size classes and equipment configuration, we divided the commercial AC systems into four categories, namely the small direct-expansion (DX) ACs and room ACs used in the NRB sector, medium-large DX ACs, large chillers, and others, as shown in Table 4. Therefore, the total refrigerant emissions, EMM, can be calculated using the following expression:

$$EMM = \sum_{i=1}^4 \sum_{j=1}^7 \sum_{k=1}^3 [C_i \times \xi_{i,j} \times SRC_{ij} \times LR_k] \quad (2)$$

Where C_i represents the capacity of the cooling equipment of type “i” (viz. small DX or split room ACs, medium-large DX, chillers, and others), $\xi_{i,j}$ the share of refrigerant type “j” (i.e., HCFC-22, HFC-410A, HFC-32, HC-290) used in the i^{th} AC equipment, SRC_{ij} the specific refrigerant charge of the i^{th} AC unit, $LR_{i,j,k}$ the leakage rate of the k^{th} process (viz. operational process, servicing process, and end-of-life process) of the refrigerant type j in the i^{th} AC unit (Liu et al., 2019; Wang et al., 2016; Li et al., 2016).

3.3 Scenario design

For the purpose of this study, reference or business-as-usual (BAU) scenario for HFC emissions in the NRB sector have been developed under the assumption that the Kigali amendment (KA) is not implemented. Although the pre-KA reference scenario may be seen as outdated and therefore uninteresting given that the KA has already entered into force, it is still necessary to first generate reference scenario as consistent bases for the construction of future emission reduction scenarios. The pre-KA reference scenario provides a primary point of reference for evaluating the need for – and impact of – alternative low-GWP technologies in the NRB sector. Therefore, the alternative mitigation scenarios developed here assume the same demand for cooling services in the NRB sector of China as in the reference but with the consumption of high-GWP HFCs replaced by alternative low-GWP technologies. The key contribution of this task is not to determine the reduction levels in HFC consumption (as these are already predetermined by the regional targets of the KA) but rather to investigate the content of the HFC phase-down in terms of the order and extent to which various alternative technologies are picked up in the NRB sector. Once we have determined the types of technology and the extent to which they are expected to be employed in the NRB sector ((Höglund-Isaksson et al., 2017), we can start quantifying the electricity savings expected from several of the technology switches that replace the use of high-GWP HFCs. Hence, in addition to the direct climate benefits of HFC emission reductions, transitioning away from HFCs can catalyze additional climate benefits through improvements in the energy efficiency of the cooling technologies that currently use HFCs in the NRB sector of China.

In order to explore the possible futures of the efficient cooling technologies used in the Chinese NRB sector, we have developed four alternative scenarios, namely the economic energy efficiency improvement of cooling technologies, EE(E) scenario, the technical energy efficiency improvement of cooling technologies, EE(T) scenario, the economic energy efficiency improvement of cooling technologies along with transition towards low-GWP refrigerants under the KA, EE(E)+KA scenario, and the technical energy efficiency improvement of cooling technologies along with transition towards low-GWP refrigerants under the KA, EE(T)+KA scenario. Under the EE(E) and EE(T) scenarios, the efficiency gains calculated are from improvements in the design and components, which can yield efficiency improvements of 10 to 70% (UNEP, 2018) and thus mostly independent of the refrigerant(s) used. The switch to lower GWP substitutes usually entails an efficiency gain of the order of 5-10% (Purohit et al, 2016; UNEP, 2018). There exist different efficiency improvement potentials of different type of cooling technologies in different scenario (see details in Table 5). In the first two alternative scenarios, we only consider the ACs system’s efficiency improvement, whereas in the last two alternative scenarios, we consider both the energy efficiency improvement of the cooling technologies (Purohit et al., 2020; Wang et al., 2020) and the efficiency improvement due to transition towards low-GWP refrigerants (Purohit et al., 2018; UNEP-IEA, 2020).

Table 5. Energy efficiency improvement potentials for different type of ACs in the alternative scenarios

Different type of ACs	EE(E)	EE(E)+KA	EE(T)	EAC(T)+KA
Small DX or split room AC ^a	30%	36%	60%	72%
Medium-Large DX ^b	32%	35%	46%	48%
Chiller ^b	23%	29%	43%	47%
Others (i.e., LiBr ACs) ^c	28%	33%	50%	56%
Total efficiency improvement	30%	34%	49%	54%

Notes: a. Energy efficiency improvement potential for Small DX or split room ACs are obtained from [Shah et al. \(2015\)](#), [Shah et al. \(2013\)](#) and [Phadke et al., \(2014\)](#).

b. Energy efficiency improvement potential for Medium-large DX and Chillers are taken from [Purohit et al. \(2020\)](#).

c. Energy efficiency improvement potential for others (i.e., LiBr ACs) is calculated from the average of other three types of ACs, including small DX, medium-large DX, and chiller.

In order to assess the energy consumption and greenhouse gas emissions related to space cooling in the Chinese NRB sector, the development trend of total cooling capacity is taken from [IEA \(2018\)](#). In addition to the energy efficiency improvement of the cooling technologies, the market share of different types of cooling technologies and the changing trend of refrigerant usage situation in different cooling equipment are also taken into account under the BAU and alternative scenarios. The share of different type of commercial cooling technologies used in the Chinese NRB sector as well as the share of different refrigerants used in various commercial cooling technologies are taken from Chinese central air conditioner market report over the years ([EIET, 2010; 2015; 2020](#)). Table S4 presents the key assumptions and data on cooling capacity, share of different types of cooling technologies and the share of different refrigerants in various scenarios in the future.

3.4 Co-benefits analysis

In this study, we assess co-benefits of space cooling in the NRB sector in the form of electricity savings and associated reductions in GHG (including the CO₂ reduction from electricity saving and CH₄ abatement from upstream electricity production), air pollutant emissions - including sulfur dioxide (SO₂), nitrogen oxides (NO_x), and fine particulate matter (PM_{2.5}) emissions, as well as short-lived climate pollutants (SLCPs) emissions reduction primarily due to the transition towards low-GWP refrigerants and enhanced efficiency of the cooling technologies. In the BAU scenario, the total energy consumption of commercial space cooling in China can be estimated by the EUI of different NRB types ([Table 3](#)) and the total commercial floor space, estimated using Eq. (1). The electricity saving potential of alternative scenarios are measured by different energy efficiency assumptions (technical and economic energy efficiency potential) due to the system's improvement and transition towards low-GWP refrigerants under the KA. The GHG emissions in the BAU scenario can be derived from the total electricity consumption of space cooling in the NRB sector multiplied by the implied emission factor, together with the HFC emissions due to the refrigerant leakage during the operation, servicing as well as end-of-life processes, and the upstream CH₄ emissions in electricity production.

The implied emission factors have been taken from the GAINS model ([Amann et al., 2008](#)), which involves series of air pollutants and GHGs from global, national as well as regional energy consumption. The implied emission factors used in this study include the CO₂ and CH₄, as well as the SO₂, NO_x, PM_{2.5} together with the short-lived climate pollutants (BC and OC) that the expected region/province- and year-specific fuel mixes used in power plants in the IEA-WEO 2018 Current Policies Scenario (CPS)², New Policies Scenario (NPS)³ and

² The CPS is based solely on existing laws and regulations as of mid-2018 and therefore excludes the ambitions and targets that have been declared by governments around the world ([IEA, 2018](#)).

³ The NPS aims to provide a measured assessment of where today's policy frameworks and ambitions, together with the continued evolution of known technologies, might take the energy sector in the coming decades. The policy ambitions include those that have been announced as of August 2018 and incorporate the commitments made in the Nationally Determined Contributions under the Paris Agreement, but do not speculate as to further evolution of these positions.

Sustainable Development Scenario (SDS)⁴, respectively, in the timeframe to 2050 (Wang et al., 2020). Further information is available in IEA (2018) and Rafaj et al. (2018).

4. Results and discussion

Using the methodology described in Section 3, we assess the energy efficiency related co-benefits in terms of electricity savings and the associated reduction in GHGs, air pollutants and SLCP emissions under different policy scenarios. In this section, the results of the energy consumption of space cooling in NRBs under BAU scenario as well as the electricity savings and associated reduction in GHGs, air pollutants and SLCPs emissions in the alternative scenarios are presented.

4.1 Energy consumption for space cooling in the non-residential building sector

The NRB sector in China is expected to grow further as the floor space is relatively low as compared with other industrialized countries. Our results indicate that under the BAU scenario, the total floor space in the NRB sector of China will reach 21.1 billion m² in 2030 and 29.2 billion m² in 2050 as compared to the 11.1 billion m² in 2015. These growth trends are consistent with the forecast of THUBERC (2018). In addition, the floor space per capita shows a significant positive correlation with the GDP per capita, and it will also maintain a continuous growth trend in near future. It is estimated that the floor space per capita will reach 14.92 m² in 2030 and 21.79 m² in 2050 as compared to 8.07 m² in 2015. The estimated floor space per capita in the NRB sector of China in 2050 is expected to reach the current level of the industrialized countries like Europe, Canada, Japan and the United States (EIA, 2021; NRC, 2017; EC, 2017; EDMC, 2016). The detailed provincial data of total floor space and floor space per capita are presented in Table S2 of the SI. The continuous growth trend of the floor space of the NRB sector in China will also bring a sustained growth in energy consumption and associated GHG and air pollutant emissions.

Our results reveal that in the BAU scenario, the energy consumption for space cooling in the Chinese NRB sector will increase from 166 TWh in 2015 to 338 TWh in 2030, and then to 564 TWh in 2050. There is significant growth potential for the space cooling in the NRB sector of China primarily due to the rapid growth of the scale in the total floor space. The detailed provincial level estimates of the total energy consumption in BAU is presented in Table S5 of the SI. The total energy efficiency improvement potential in alternative scenarios analyzed in this study is estimated using the a) shares of different types of cooling technologies, and b) energy efficiency improvement potentials for different types of cooling technologies (Table 5). It is assumed that the share of different types of cooling technologies in near future will remain at the 2020 level, viz. small DX or split room AC (25%), medium-large DX (50%), chillers (20%), and others (5%) (HVACRHOME, 2011; HVACRHOME, 2015; HVACRHOME, 2018). In addition, the technical losses in the power transmission and distribution process are also taken into account (Wang et al., 2020; Lin et al., 2018; Depuru et al., 2011).

In view of the above, the electricity saving potential for space cooling in the Chinese NRB sector under the four alternative scenarios analyzed in this study is shown below in Figure 7. As compared to the BAU scenario, the energy saving potential under EE(E) scenario in 2030 and 2050 is estimated at 53 TWh and 176 TWh, respectively. The major contribution to the energy saving in the EE(E) scenario is due to the improvement in energy efficiency of cooling technologies using efficient compressors, heat exchangers, valves etc. that will finally lead to the reduction in the energy consumption of the cooling technologies in the NRB sector. Similarly, the energy saving potentials in EE(E)+KA scenario is estimated at 87 TWh in 2030 and 292 TWh in 2050 respectively. Under the technical energy efficiency improvement EE(T) scenario, the energy saving potentials is estimated at 61 TWh in 2030 and 202 TWh in 2050 respectively. The energy saving potentials in EE(T)+KA scenario is estimated at 97 TWh in 2030 and 322 TWh in 2050 respectively.

⁴ The SDS is fully aligned with the a) Paris Agreement's goal of holding the increase in the global average temperature to "well below 2 °C", b) Achieving universal access to modern energy by 2030 and c) reducing dramatically the premature deaths due to energy-related air pollution.

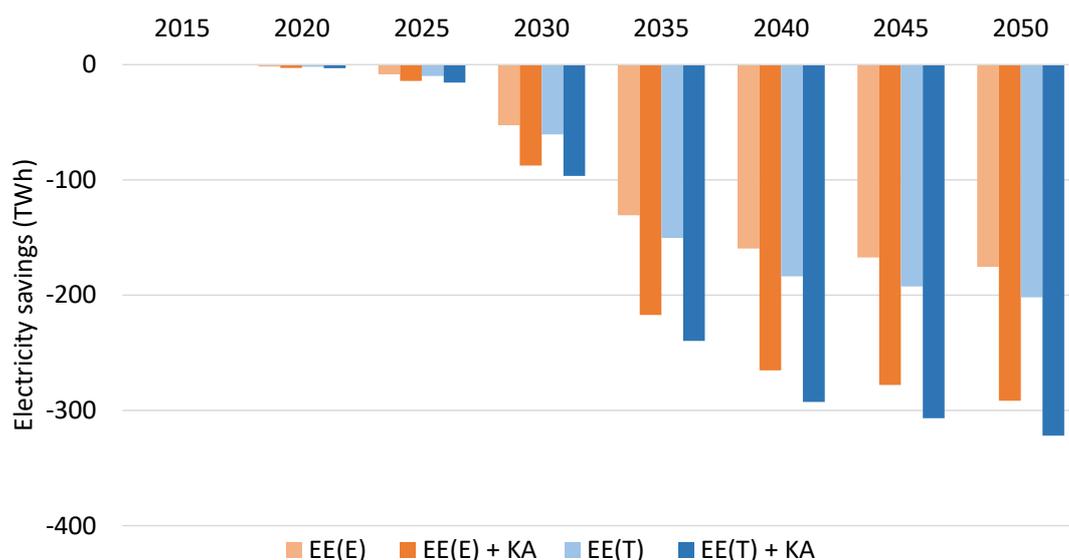


Figure 7. Electricity savings in the alternative scenarios as compared to those in the BAU scenario

The detailed provincial data of electricity saving potential under alternative scenarios is presented in [Table S6](#). By 2050, the top three provinces with the largest electricity saving potential are Guangdong, Jiangsu and Shanghai, with the potentials of 39 TWh, 31 TWh and 26 TWh respectively, accounting for about 30% of the total electricity saving in 2050. In 2050, under the EE(T)+KA scenario, the energy saving potential due to energy efficiency improvement and the transition to the low-GWP refrigerants is estimated at 322 TWh that is equivalent to approximately 2% of the total building energy consumption in 2050 and potentially reduce the construction of 120 thermal power plants with an installed capacity of 500 MW with a capacity of 80% ([CABEE, 2016](#)).

4.2 GHG mitigation potential through space cooling in non-residential buildings

[Figure 8](#) presents the GHG emissions and mitigation potential in the alternative scenarios as compared to BAU scenario in 2030 and 2050. In the BAU scenario, the total GHG emissions related to the use of space cooling technologies in the NRB sector will increase from 219 Mt CO₂eq in 2015 to 325 Mt CO₂eq in 2030 and 539 Mt CO₂eq in 2050. HFC emissions through the space cooling technologies will increase from 156 Mt CO₂eq in 2015 to 203 Mt CO₂eq in 2030 and 292 Mt CO₂eq in 2050, accounting for approximately two third of the total GHG emissions. This clearly indicates that high-GWP refrigerants in air-conditioning of NRBs have a very large impact on total GHG emissions from this sector. Transitioning to low-GWP or natural refrigerants (i.e., water, CO₂, hydrocarbons) under the Kigali Amendment will contribute significantly to achieving the carbon neutrality goal of the Chinese government by 2060 ([UN News, 2020](#); [UNEP-IEA, 2020](#); [CCPCC, 2021](#)). Under the EE(T)+KA scenario, the CO₂ and CH₄ (methane) mitigation potential due to technical energy efficiency measures of cooling technologies is estimated at 141 Mt CO₂eq by 2050. In addition, HFC mitigation potential due to transition towards low-GWP refrigerants is estimated at 260 Mt CO₂eq by 2050. Therefore, considering both the energy efficiency improvements and transition towards low-GWP refrigerants of space cooling technologies in the NRB sector of China, the total GHG mitigation potential will reach 401 Mt CO₂eq in 2050, which is approximately equal to 10% of Chinese total carbon emissions of the building sector in 2050.

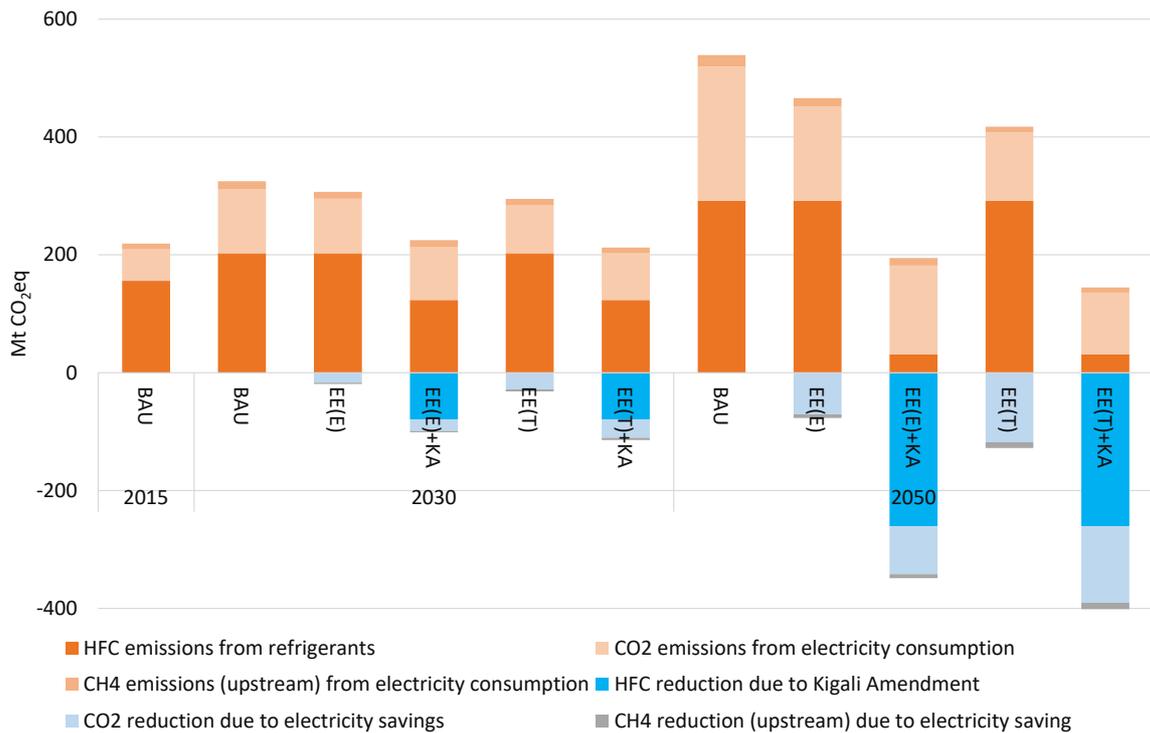


Figure 8. GHG emissions and mitigation potential in the alternative scenarios as compared to the BAU scenario.

The detailed provincial data of GHG mitigation potential due to the enhanced energy efficiency of non-residential space cooling technologies along with substitution of high-GWP refrigerants by low-GWP refrigerants under the KA is shown in Figure 9 and Table S6 of the SI. It is observed that the regions with the greatest GHG mitigation potential are Guangdong, Jiangsu and Shanghai provinces. Note that these three regions are all in the HSWWR and HSCWR climate zones with a forefront economic development level of China, indicating that the use of cooling technologies is greatly affected by regional economic development and climatic conditions. 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).

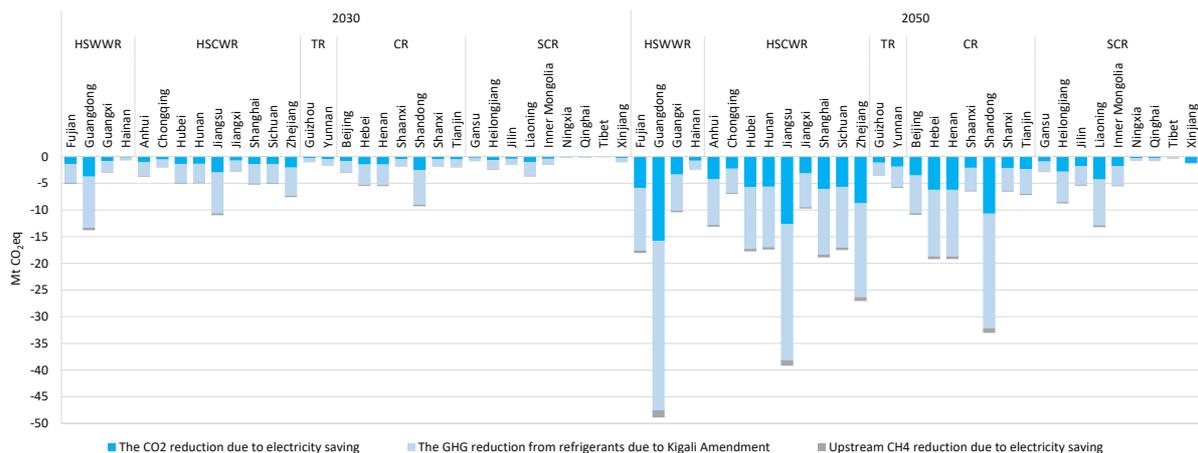


Figure 9. The provincial GHG mitigation potential in EE(T)+KA scenario

In addition, the GHG mitigation potential under the alternative policy scenarios are also estimated using the implied emission factors for power sector under current policies scenario (CPS), new policies scenario (NPS), and sustainable development scenarios (SDS), as explained in IEA (2018). Figure 10 presents the GHG mitigation potential in alternative scenarios using CPS, NPS and SDS variants of the implied emission factors (see Figure S3 for details). The detailed information on the transition trends towards low-GWP refrigerants and the share of

different refrigerant types that will be used in Chinese non-residential cooling systems in the future is presented in Table S4. In addition, the GHG mitigation potential in alternative scenarios is estimated by using key assumptions and data presented in Table S4.

In EE(E)+KA scenario, the GHG mitigation potential of space cooling technologies in the Chinese NRB sector will reach 101 Mt CO₂eq in 2030 and 349 Mt CO₂eq in 2050. Similarly, under the EE(T)+KA scenario, the GHG mitigation potential is estimated at 114 Mt CO₂eq in 2030 and 401 Mt CO₂eq in 2050 respectively using the implied emission factors from the IEA's currently policies scenario. Noted that the GHG mitigation potential in NPS and SDS scenarios is lower as compared to the CPS scenario, due to the high penetration of renewable energy and energy efficiency measures in the NPS and SDS scenarios.

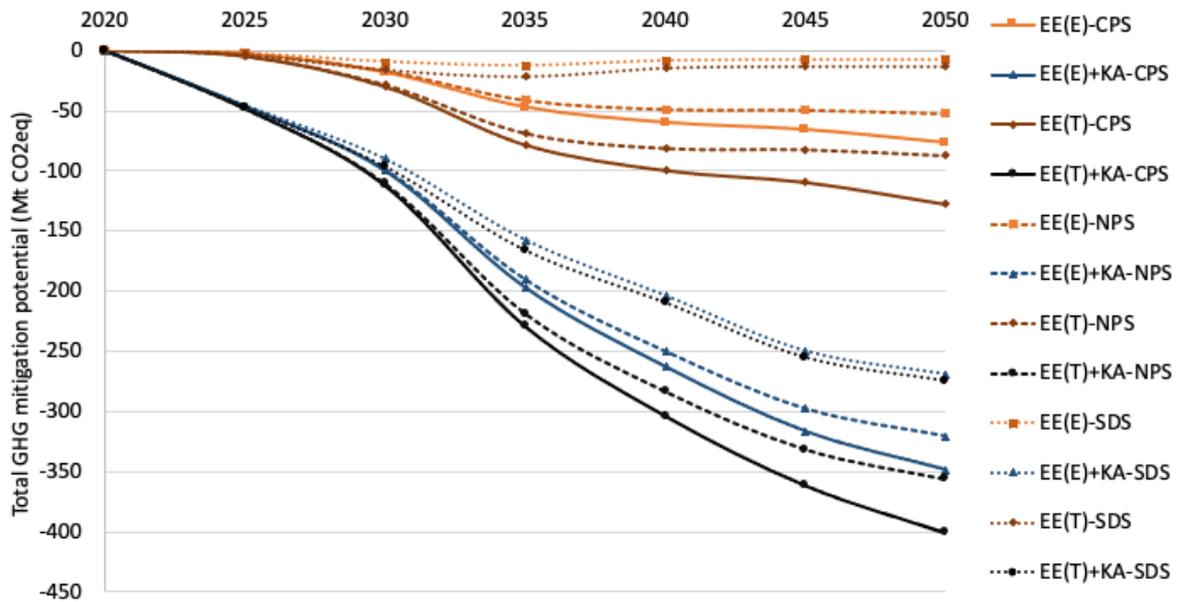


Figure 10. GHG mitigation potential in alternative scenarios

4.3. Impact on air pollutants and SLCPs emissions

Apart from the benefits of energy saving and GHG mitigation, the usage of energy efficient air conditioning in the Chinese NRB sector can indirectly lead to the reduction of air pollutant emissions and SLCPs emissions through the reduced electricity consumption, which can improve the air quality and have a positive effect on public health. The emission reductions of SO₂, NO_x, and PM_{2.5} as well as SLCPs are shown in Figure 11. Under the EE(T)+KA scenario the SO₂, NO_x and PM_{2.5} emissions reduction potential in the Chinese NRB sector is estimated at 43 kt SO₂, 73 kt NO_x and 12 kt PM_{2.5} in 2050. The SO₂ and NO_x emitted by the power plants have a huge impact on environmental quality and will directly lead to the formation of secondary particulates. In addition, the emission reduction potential of black carbon and organic carbon are also shown in Figure 11. In EE(T)+KA scenario, the emission reduction potential of black carbon and organic carbon is estimate at 0.2 tons and 0.9 kt in 2050, respectively. The detailed provincial data of air pollutants and SLCPs reduction potential can be seen in Table S7 of the SI.

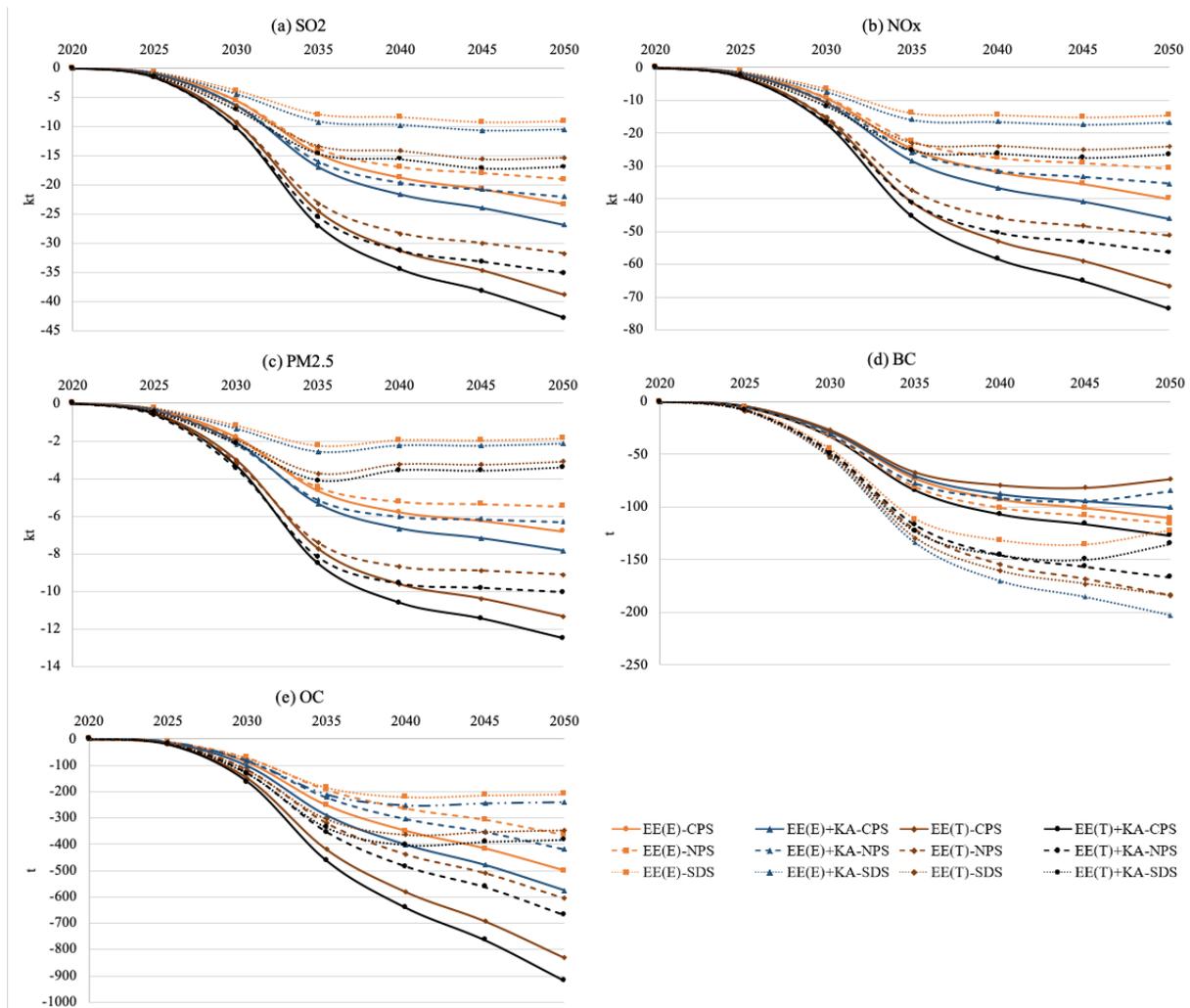


Figure 11. The air pollutants and SLCPs emission reduction of different policy scenarios in 2050

5. Conclusions and policy implications

In this study, we have used the GAINS model framework to estimate current and future emissions of hydrofluorocarbons and their abatement potentials for space cooling in the non-residential building (NRB) sector of China and assess the co-benefits in the form of savings in electricity and associated reductions in greenhouse gas (i.e., CO₂ and CH₄), air pollutants (i.e., SO₂, NO_x and PM_{2.5}) and short-lived climate pollutants (i.e., BC, OC) emissions. The energy demand for the space cooling in the NRB sector is increasing significantly primarily due to the rapid growth of commercial floor space in China. Our results indicate that the growth of the floor space in the NRB sector will exceed 1.5 times in 2050 as compared to 2015. The result and conclusions can be illustrated as follows:

- Under the BAU scenario, the total energy consumption for space cooling in the NRB sector of China, will increase from 166 TWh in 2015 to 338 TWh in 2030 to 564 TWh in 2050, primarily due to the rapid increase in the floor space area of NRBs. The floor space of NRBs in China will increase from 11.1 billion m² in 2015 to 21 billion m² in 2030 to 29 billion m² in 2050. As compared to the BAU scenario, the energy saving potential in the technical energy efficiency improvement of the cooling technologies along with transition of low-GWP refrigerants, i.e., EE(T)+KA scenario will increase from 97 TWh in 2030 to 322 TWh in 2050. By 2050, under the EE(T)+KA scenario, the energy saving potential of the space cooling of NRBs in China will be equivalent to about 2% of the total building energy consumption in 2050, which can reduce the construction of 120 thermal power plants with an installed capacity of 500 MW with a capacity factor of 80%.

- The greenhouse gas emissions from the space cooling of the NRBs of China will increase from 219 Mt CO₂eq in 2015 to 325 Mt CO₂eq in 2030 to 539 Mt CO₂eq in 2050 under the BAU scenario. The direct GHG emissions from HFCs will increase from 156 Mt CO₂eq in 2015 to 203 Mt CO₂eq in 2030 to 292 Mt CO₂eq in 2050 under the BAU scenario, accounting for more than 50% of the total GHG emissions. GHG mitigation potential in EE(T)+KA scenario ranges from 114 Mt CO₂eq in 2030 to 401 Mt CO₂eq in 2050 as compared to the BAU scenario. The total GHG mitigation potential under the EE(T)+KA scenario is approximately equal to 10% of the total carbon emissions of the building sector of China in 2050.
- The reduction in energy consumption due to the energy efficiency improvement of cooling technologies used in the NRB sector can also indirectly reduce the emissions of SO₂, NO_x and PM_{2.5} from power sector. SO₂ emission reduction potential in EE(T)+KA scenario is estimated at 43 kt SO₂ by 2050, NO_x emission reduction potential is about 73 kt NO_x, and PM_{2.5} emission reduction potential is about 12 kt PM_{2.5} as compared to the BAU scenario. In the EE(T)+KA scenario, the emission reduction potentials of black carbon and organic carbon by 2050 is estimated at 0.2 kt BC and 0.9 kt OC respectively as compared to the BAU scenario.

By 2050, GHG mitigation potential from the replacement of high-GWP refrigerants accounted for more than 50% of the total GHG reduction in EE(T)+KA scenario as compared to the BAU scenario, indicating that the use and leakage of current refrigerants in space cooling technologies in NRBs has a very large impact on total GHG emissions. If China can effectively control and improve the conversion and substitution of refrigerants under the Kigali Amendment to the Montreal Protocol the NRB sector will make an important contribution to the mitigation of GHG emissions in China. In the context of the Kigali Amendment, the results of energy-saving and emission-reduction of space cooling technologies in the NRB sector are slightly different from those of residential air-conditioning (Wang et al., 2020), due to the large cooling capacity and the refrigerant charge of air-conditioning units in the NRB sector.

The space cooling demand in the residential and commercial sector of China is set to increase even more substantially in the coming decade, especially as urban residential and commercial households move towards more energy-intensive cooling behavior and as summer heat drives up demand for cooling services. China can take immediate action to rein in the growth in energy use while allowing for continued improvement in thermal comfort. Well-defined policy actions can deliver significant electricity savings and GHG mitigation as well as reduced local air pollution by ensuring the widespread deployment of high-performance cooling, including the equipment and systems themselves, as well as measures to improve building design and address the underlying need for cooling energy use.

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Data availability Data is available on supplementary material.

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