

<https://doi.org/10.1038/s41612-025-01289-1>

Cooling China without warming the planet: climate and co-benefits of HFC phase-down



Pengnan Jiang^{1,2}✉, Pallav Purohit², Xueying Xiang³, Ziwei Chen¹, Fuli Bai¹, Xingchen Zhao¹, Xu Zhang¹ & Jianxin Hu¹✉

China's rapidly expanding cooling sector is a major driver of greenhouse gas (GHG) emissions and rising electricity demand, with profound implications for national decarbonization goals and global climate targets. Using a bottom-up, scenario-based model, we quantify direct refrigerant-related and indirect energy-related emissions across four subsectors: room air conditioning, mobile air conditioning, commercial air conditioning, and cold-chain refrigeration. Compared with a business-as-usual (BAU) scenario for 2022–2060, an accelerated transition to low-GWP refrigerants and enhanced energy efficiency (ATE) is projected to reduce cumulative HFC consumption by 12.6 ± 0.4 Gt CO₂-eq, with 70% of these reductions achieved through compliance with the Kigali Amendment and the remainder from faster adoption. The ATE pathway would also avoid 4.1 Gt CO₂—~28% of total avoided GHG emissions—along with substantial reductions in SO₂ (1.8 Gt), NO_x (3.7 Gt), and PM_{2.5} (0.3 Gt), lowering global mean temperature by up to 0.015°C by 2060. These results demonstrate the additional climate benefits achievable when efficiency improvements are implemented alongside Kigali-compliant refrigerant transitions.

Energy consumption in the cooling sector is rapidly increasing due to rising global temperatures, economic development, and urbanization, which also show pronounced inequalities in per-capita cooling energy use across regions¹. The cooling sector—primarily through air conditioning—and refrigeration² systems demand significant electricity, much of which is still generated from fossil fuels. It plays a critical role in addressing the increasing frequency of extreme heat events^{3–5} and contributing to the achievement of the United Nations Sustainable Development Goals⁶. However, the rapid expansion of this sector has also intensified global warming¹. Cooling technologies extensively rely on hydrofluorocarbons (HFCs) as substitutes for ozone-depleting substances (ODS) regulated under the Montreal Protocol. Although HFCs are effective refrigerants, their high global warming potentials (GWPs) pose significant challenges to climate mitigation. In 2022, greenhouse gas (GHG) emissions related to the refrigeration, air conditioning, and heat pump (RACHP) sector accounted for approximately 13% of global GHG emissions^{7,8}, with direct emissions from refrigerants contributing nearly 30% of this total⁸.

In addition to direct emissions from refrigerant leakage, indirect carbon dioxide (CO₂) emissions from the energy consumption of RACHP equipment are equally significant. As of 2024, an estimated 5.4 billion

RACHP systems were in operation globally, consuming around 20% of total global electricity⁹. During extreme heat events that coincide with peak cooling demand, the energy consumption of air conditioning systems in residential and commercial buildings imposes substantial stress on power grids¹⁰ and can significantly alter long-term mitigation pathways¹¹. Despite growing demand, the energy efficiency (EE) of most air conditioners currently on the market remains at about one-third to one-half of the best available technologies¹², underscoring substantial untapped potential for energy savings within the sector.

If left unchecked, the continued growth of the cooling sector could consume a significant share of the carbon budget aligned with the climate goals of the Paris Agreement within the next 30 years¹³. Unabated emissions of HFCs alone are projected to contribute an additional 0.3–0.5 °C to global surface temperatures by 2100^{14,15}. In contrast, strict implementation of the Kigali Amendment (KA) to the Montreal Protocol could limit this contribution to below 0.1 °C¹⁶. Nevertheless, the current reduction targets under the KA are insufficient to fully align with the Paris Agreement's long-term temperature goal¹⁷, and under existing policies, HFCs will remain a major mitigation challenge. Existing studies indicate that an accelerated HFC phase-down could provide substantial additional climate benefits¹⁸.

¹College of Environmental Sciences and Engineering, Peking University, Beijing, China. ²Pollution Management Research Group, Energy, Climate, and Environment (ECE) Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria. ³Department of Civil and Environmental Engineering, National University of Singapore, Singapore, Singapore. ✉e-mail: pnjiang@pku.edu.cn; jianxin@pku.edu.cn

Therefore, accurately projecting future demand, assessing emission reduction potentials, and formulating effective mitigation pathways are critical to achieving global climate targets. With global cooling demand expected to triple by 2050 relative to 2018², addressing both energy efficiency and refrigerant management is critical for climate change mitigation³.

At the 28th Conference of the Parties (COP28) to the United Nations Framework Convention on Climate Change (UNFCCC), over 50 countries committed to reducing cooling-related GHG emissions by 68% by 2050 (relative to 2022 levels), highlighting the urgency of promoting sustainable cooling solutions¹⁹. While regulatory frameworks under the Kyoto and Montreal Protocols have increasingly target fluorinated gases, significant data gaps remain in many countries regarding HFC consumption and emissions. Accurate estimates of HFC use and emissions are now essential for international compliance. Given the cooling sector's large share of HFC use, there are considerable opportunities to reduce HFC emissions while improving energy efficiency. Research indicates that combining refrigerant transitions with the deployment of high-efficiency equipment can more than double the short-term climate benefits of HFC mitigation¹³ and reduce projected electricity demand by up to 20%²⁰.

Against the backdrop of rising global temperatures and surging cooling demand, China stands at the center of the climate-cooling nexus. As the world's largest producer and a leading consumer of cooling equipment—manufacturing over 80% of global room air conditioners and consuming half domestically²¹—China's cooling sector is poised to significantly shape global climate outcomes. Already accounting for an estimated 15% of national electricity use²², China's cooling energy demand is expected to rise sharply, mirroring trends across emerging economies like India and Indonesia, which together comprise nearly 50% of global space cooling needs^{13,23–26}. With ongoing climate change and rising household income, this share is expected to grow even further in the coming decades²⁷.

Despite this critical context, existing studies largely focus on individual subsectors^{5,28–31} or treat refrigerant transition and energy efficiency in isolation missing the synergistic benefits of integrated strategies. Moreover, comprehensive bottom-up emission inventories remain limited, constraining the development of effective, evidence-based policies³². This study addresses these gaps by delivering the first comprehensive, bottom-up assessment of China's cooling sector across four major subsectors: room air conditioners (RAC), mobile air conditioning (MAC), commercial air conditioning (CAC), and the cold chain refrigeration (CCR) systems. We quantify both direct (refrigerant related) and indirect (energy related) emissions, evaluate future trajectories, and estimate the cooling sector's contribution to global warming. Importantly, we identify co-benefits—including energy savings and substantial reductions in emissions of air pollutants such as fine particulate matter (PM_{2.5}), sulfur dioxide (SO₂), and nitrous oxides (NO_x)—thus providing a robust scientific foundation for integrated climate and energy policy at the national level.

Results

Cooling demands forecasts

Building on the comprehensive framework outlined in the Methods section, this section provides detailed projections of future cooling demand across China's four major cooling subsectors. Demand growth across these subsectors is shaped by a combination of socioeconomic and sector-specific drivers—including population growth, urbanization, rising household incomes, increasing ambient temperatures, commercial building development, and cold chain infrastructure expansion. These projections offer essential insights for designing targeted mitigation strategies and energy efficiency policies.

In the RAC subsector, future demand is predominantly driven by population changes, urbanization, rising household incomes, and increasing ambient temperatures. Nationally, RAC unit stock is projected to expand significantly until around 2030, approaching market saturation by approximately 2040, with a peak of about 1.1 billion units (Fig. 1a). Thereafter, demand begins to fluctuate due to demographic shifts—particularly aging and slowing population growth—with urban unit stocks

continuing to grow while rural stocks gradually decline. This pattern reflects ongoing urbanization, where rural populations migrate into cities, leading to reclassification of demand rather than an absolute decrease. Compared with international projections, our forecasts for the RAC subsector closely align with International Energy Agency (IEA) estimates before 2030²⁵. However, after 2030, the IEA projects substantially higher stock growth, which may be attributed to differences in long-term assumptions regarding household income and population dynamics. In contrast, the post-2030 growth trajectory presented by Collaborative Labeling and Appliance Standards Program (CLASP) is slower than ours, although the long-term saturation levels are broadly similar³³. This divergence likely stems from differing assumptions about the saturation thresholds of RAC stock.

Projections for the MAC subsector, disaggregated into passenger cars, buses, and trucks, indicate a peak around 2035, with the total stock approaching 700 million units (Fig. 1b). Demand growth is shaped by province-level differences in income, population dynamics, and transport-related policies, which influence vehicle ownership rates and fleet composition. Passenger cars represent the largest segment, whereas trucks and buses, although smaller in absolute terms, display distinct trajectories influenced by transport policies and vehicle fleet turnover.

In the CAC subsector, equipment-specific modeling includes unitary systems, variable refrigerant flow (VRF) systems, centrifugal chillers, and screw chillers. Unitary and VRF systems maintain the largest market shares due to their flexibility in retail and office buildings. Although centrifugal and screw chillers represent a small fraction of total equipment stock—less than 5% as shown in Fig. 1c—they account for a disproportionate share of refrigerant use, with average charge sizes over 50 times higher than typical unitary systems. These high charge volumes contribute significantly to the CAC subsector's total refrigerant emissions, underscoring their environmental relevance despite limited stock share.

Driven by diverse equipment types, the CCR subsector is anticipated to undergo consistent growth. Among the analyzed end-use categories—including display cabinets, refrigerated vending machines, commercial ice makers, medical refrigerators, and ice cream machines—self-contained commercial refrigerators represent the largest equipment segment. Furthermore, cold-storage capacity, a key indicator of systemic refrigeration infrastructure, is projected to double by 2050, highlighting the sector's increasing importance in food security and climate mitigation (Fig. 1d).

Overall, these subsector-specific demand projections provide a robust quantitative foundation for assessing mitigation potential, prioritizing policy interventions, and guiding the development of regionally differentiated energy efficiency standards.

Scenario-based analysis of refrigerant and emission trends

Using a bottom-up modeling approach, this section presents scenario-based projections of refrigerant consumption and direct emission trends across China's cooling subsectors under three policy scenarios (business-as-usual-BAU, Kigali Amendment with enhanced energy efficiency-KAE, and accelerated transition to low-GWP refrigerants and enhanced energy efficiency-ATE), as shown in Fig. 2.

Figure 2a illustrates that, historical HFC consumption grew rapidly alongside rising cooling demands, reaching approximately 666.5 Mt CO₂-eq in 2022 according to data reported by China to the Ozone Secretariat³⁴. While this value exceeds the estimate by Bai et al.³⁵(553.5 Mt CO₂-eq), the two figures are broadly comparable given methodological differences. About 70% of China's total HFC consumption in 2022 was for air-conditioning applications, with RACs contributing the largest share. However, due to the rapid adoption of low-GWP refrigerants, HFC consumption in CACs is projected to surpass that of RACs in the coming decades (see Fig. S6), followed by MAC and CCR. Additionally, the analysis highlights significant progress in phasing out HCFC-22 in these subsectors, marking a transition away from refrigerants with high ozone depletion potentials.

As a Group 1 Article 5 Party to the Kigali Amendment, China has initiated formal controls on HFC consumption from 2024, with the national

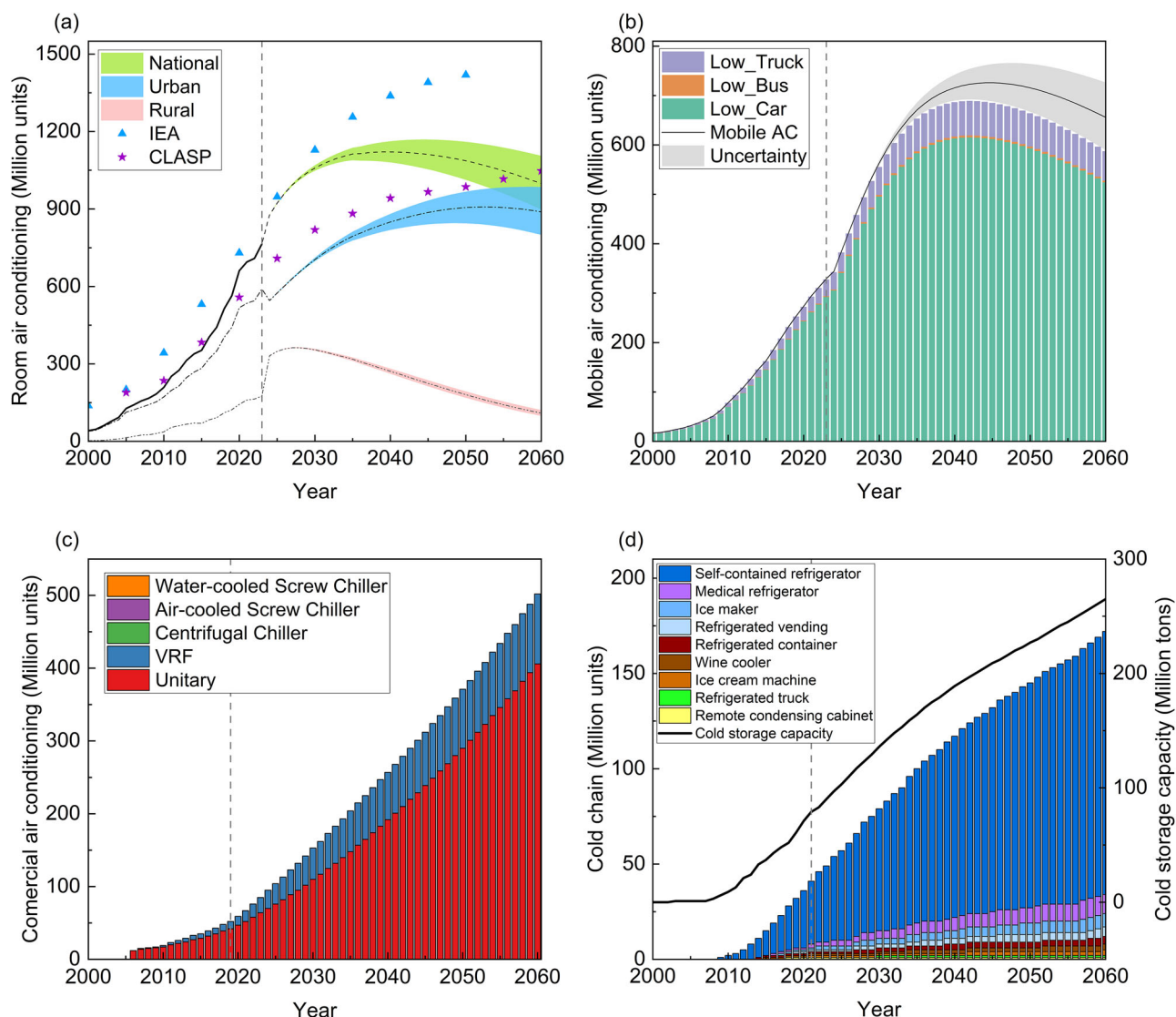


Fig. 1 | Historical and projected stock of cooling equipment by subsector in China (2000–2060). **a** RACs, including national, urban, and rural stock estimates. Shaded areas represent uncertainty ranges. **b** MACs, including passenger cars, buses and trucks. Colored bars represent stock estimates for each vehicle type under the lower

bound of the uncertainty range, while the gray shaded area reflects the full uncertainty envelope. **c** CACs, categorized by equipment type. **d** CCR equipment, where the black line represents the total cold-storage capacity (right axis), and colored bars show the number of refrigeration units (left axis).

baseline established at 905 Mt CO₂-eq³⁶. Our results indicate substantial reductions in refrigerant consumption under the KAE, achieving a cumulative decrease of 9.2 ± 0.3 Gt CO₂-eq relative to BAU over 2022–2060. The ATE scenario—which assumes a complete phase-out of new HFC-based equipment by around 2040 and limits subsequent HFC consumption to servicing needs—achieves an additional 3.4 ± 0.1 Gt CO₂-eq reduction compared with KAE, bringing refrigerant-related emissions close to zero by mid-century. Notably, according to China's National Implementation Plan for the Montreal Protocol (2025–2030), the use of HFC refrigerants will be prohibited in newly manufactured passenger cars starting in 2029, marking a regulatory milestone in China's sectoral HFC phase-down efforts³⁶. These measures collectively contribute to achieving the country's long-term carbon neutrality objectives.

Figure 2b illustrates the trajectory of direct refrigerant emissions under the three scenarios. In the BAU scenario, emissions continue rising due to ongoing equipment deployment and low refrigerant recovery rates at the end of the equipment's life cycle. In contrast, under the KAE scenario, emissions peak around 2027 at approximately 277.0 ± 9.6 Mt CO₂-eq before gradually declining, achieving a cumulative reduction of 7.3 ± 0.3 Gt CO₂-eq from 2022 to 2060 relative to

BAU. Under the more ambitious ATE scenario, emissions significantly decrease after 2025, approaching near-zero levels by 2060, with a cumulative reduction of an additional 3.1 ± 0.1 Gt CO₂-eq beyond the KAE scenario. Notably, despite an earlier decline in HFC consumption in the KAE and ATE scenarios, the peak of refrigerant emissions occurs several years later, reflecting time lags due to equipment use-phase leakage and delayed end-of-life emissions.

A subsector-specific analysis reveals that CACs possess the largest potential for cumulative direct emission reductions, contributing approximately 47% under the KAE scenario, followed by MAC at 32%. The CCR sector, particularly remote condensing units and other large-scale refrigeration equipment, as well as the CAC subsector, large chiller units, remain critical due to their substantial refrigerant charges per unit and considerable barriers to equipment replacement. Among specific refrigerants, HFC-134a and HFC-410A are projected to dominate emission reductions, accounting for 48% and 26% respectively under KAE, and 34% and 41% respectively under ATE. Meanwhile, HFC-32, characterized by a relatively low-GWP and growing market presence, is expected to play a prominent transitional role. Effective management of HFC-32 emissions—particularly in large-scale applications such as

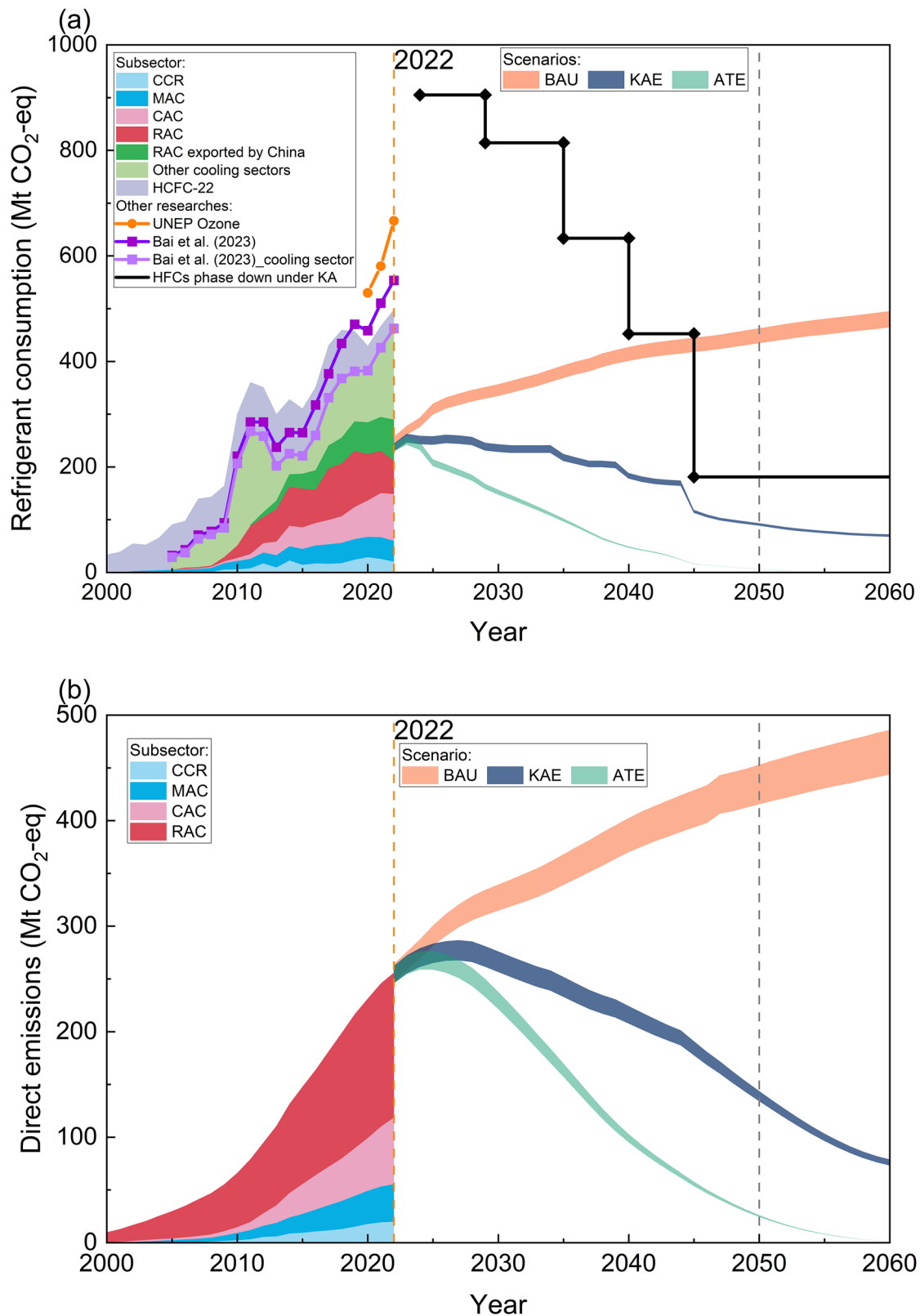


Fig. 2 | Historical and projected refrigerant consumption and direct emissions in China's cooling sectors, 2000–2060. a Sectoral refrigerant consumption trajectories under three mitigation scenarios: BAU, KAE, and ATE; and **(b)** Sectoral direct

emissions under different scenarios, highlighting divergence in peak timing and reduction pathways.

chillers—will therefore be critical to achieving deeper reductions envisaged in the ambitious ATE scenario.

The propagation of uncertainties from key parameters related to activity levels and emission factors to the final emission estimates was

quantified using a Monte Carlo framework, and a comparison with previous Chinese studies was performed to validate the model-derived historical emissions (see Supplementary Information Fig. S8).

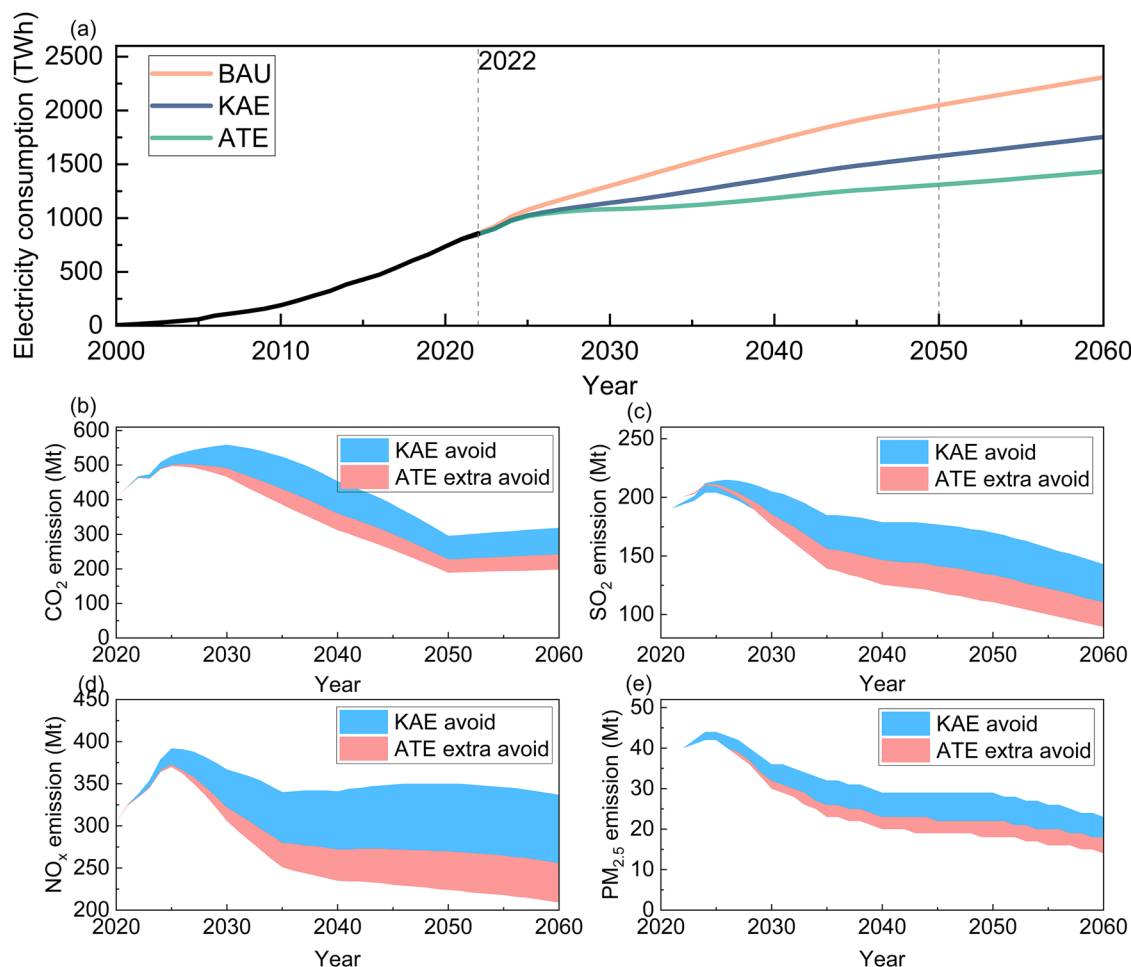


Fig. 3 | Projected electricity consumption and associated emission co-benefits from the cooling sector under three scenarios in China (2000–2060). **a** Electricity consumption under BAU, KAE, and ATE scenarios; **(b–e)** Avoided emissions of CO₂,

SO₂, NO_x, and PM_{2.5} resulting from reduced electricity demand under KAE (light blue) and ATE (red) scenarios relative to BAU. The shaded areas represent cumulative reductions, with ATE offering larger mitigation benefits across all pollutants.

Energy efficiency driven co-benefits across alternative scenarios

Under the BAU scenario, electricity consumption in China's cooling sector is projected to continue rising, potentially exceeding 2000 TWh by 2050 (Fig. 3a). In contrast, the KAE and ATE scenarios, both of which incorporate more stringent energy performance standards and accelerated market transformation efforts, demonstrate significantly reduced electricity growth. Over the period 2022–2060, these scenarios yield cumulative electricity savings of approximately 12.8 PWh (20%) and 19.6 PWh (30%) relative to the BAU case. These savings correspond to approximately 1.3 and 2.0 times China's total electricity consumption in 2024 under the KAE and ATE scenarios, respectively, underscoring the substantial potential for reducing national grid demand through efficiency-driven measures. According to the International Energy Agency (IEA)³⁷, considerable opportunities remain to further enhance the energy efficiency of cooling equipment in China, suggesting that even the projected savings could be conservative if more aggressive efficiency policies are adopted.

These reductions in electricity use translate into substantial co-benefits for emissions mitigation, particularly in the short to medium term when fossil-based generation continues to dominate the marginal electricity supply. Figure 3b–e illustrate the associated reductions in CO₂ and key air pollutants under each scenario. Specifically, under the ATE scenario, cumulative avoided emissions between 2022 and 2060 amount to approximately 4.1 Gt CO₂, 1.8 Gt SO₂, 3.7 Gt NO_x, and 0.3 Gt PM_{2.5} relative to BAU. These benefits are especially pronounced from 2025–2040, a period that will see a continued reliance on coal-based

power and provide immediate public health benefits from cutting electricity demand. Although China's power sector is undergoing rapid decarbonization—driven by the national dual-carbon strategy^{38,39}, with projections suggesting that the share of non-fossil electricity could reach approximately 80% by 2035⁴⁰—peak cooling loads during summer months remain a major source of pressure on the national electricity grid.

Overall, decarbonizing the cooling sector represents not only a strategic opportunity for climate change mitigation but also a pivotal mechanism for improving urban air quality, relieving grid stress, and alleviating related health risks. Strengthening minimum energy performance standards (MEPS) for cooling equipment will be essential—not only to lock in long-term electricity savings, but also to mitigate the risks associated with peak load growth and system instability. A coordinated strategy that simultaneously promotes refrigerant substitution and energy efficiency improvement—the “dual engines” of sustainable cooling—will be critical for fully realizing these synergistic benefits.

Temperature response under alternative mitigation scenarios

Extending our scenario-based analysis of direct and indirect emissions from China's cooling sector, we further estimate their combined contributions to global mean surface temperature rise (Fig. 4).

Figure 4a illustrates projected trajectories of aggregated emissions from 2000 to 2060. Under the BAU scenario, emissions continue rising due to increased refrigerant consumption and escalating electricity demand, peaking around 2030 at approximately 886.1 Mt CO₂-eq. Following this

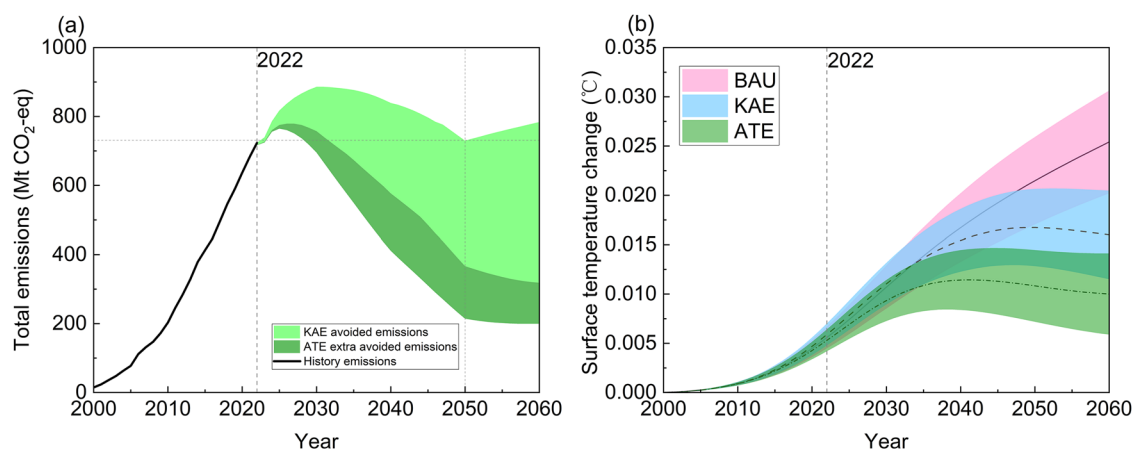


Fig. 4 | Climate impacts of China's cooling sector under different mitigation scenarios: emission trajectories and temperature response. **a** Annual combined emissions from refrigerants and electricity-related CO₂ between 2000 and 2060, illustrating emission reductions under KAE and ATE scenarios compared to BAU;

b Projected contributions of the cooling sector to global mean surface temperature rise under each scenario. Shaded areas represent uncertainty ranges. The ATE scenario achieves the largest mitigation impact, reducing the sector's warming contribution by approximately 0.015 °C by 2060.

peak, emissions decline modestly, primarily due to the projected reduction in the carbon intensity of power generation, but remain persistently elevated in the absence of additional refrigerant control or efficiency policies. In contrast, the KAE scenario achieves an earlier emissions peak around 2025, subsequently experiencing a more substantial decline. The ATE scenario further accelerates mitigation, reaching a lower peak and a steeper subsequent decline, approaching near-zero emissions by mid-century, contingent on power-sector decarbonization progress. These emission trajectories underpin corresponding differences in projected temperature impacts.

Figure 4b presents the resulting contributions to global temperature rise under each scenario. Without additional mitigation measures (BAU), cumulative cooling-sector emissions could increase global surface temperatures by 0.025 ± 0.005 °C by 2060, driven by continued use of high-GWP refrigerants and fossil-intensive electricity generation. Under the KAE scenario—characterized by adherence to the KA targets combined with moderate energy efficiency improvements—this warming contribution is reduced to 0.016 ± 0.004 °C. The ATE scenario constrains projected warming to 0.010 ± 0.004 °C by 2060, representing a reduction of more than 0.015 °C relative to the BAU.

Notably, distinct temporal dynamics characterize the temperature responses associated with direct and indirect emissions. As short-lived climate pollutants, HFCs generate immediate warming impacts, but rapid mitigation can yield substantial near-term temperature reductions—particularly evident during 2025–2045. This early mitigation creates a valuable “cooling window” that can be strategically leveraged. Among HFC refrigerants, HFC-410A and HFC-134a contribute most significantly to short-term warming; thus, prompt reductions of these substances are crucial for maximizing near-term climate benefits. In contrast, indirect CO₂ reductions from electricity use, although slower to manifest, dominate long-term temperature trajectories due to CO₂'s cumulative atmospheric effect. These differential dynamics underscore the importance of a dual-pathway approach targeting both short-lived HFCs and persistent CO₂ emissions to achieve robust, sustained temperature stabilization.

Additionally, the relative influence of direct versus indirect emissions shifts over time. Under the KAE scenario, direct emissions dominate temperature impacts initially but gradually decline as refrigerant phase-down progresses, reaching roughly equal contributions with indirect emissions by around 2050. Under the more aggressive ATE scenario, this crossover point occurs earlier, around 2040, after which indirect, electricity-related CO₂ emissions become the predominant driver of temperature rise. This evolution highlights the growing importance of power-sector decarbonization

strategies in sustaining long-term climate benefits once rapid gains from refrigerant transition are achieved.

The cooling sector's unique combination of high-GWP refrigerants, concentrated peak electricity demand, and rapid growth trajectory positions it as a strategically important lever for climate change mitigation. The ATE scenario, closely aligned with China's carbon neutrality goals, demonstrates that concurrent refrigerant substitution and electricity-sector decarbonization could nearly eliminate the cooling sector's climate impacts by mid-century, providing tangible contributions toward global climate stabilization efforts.

Discussion

This study provides a comprehensive analysis of HFC consumption, direct and indirect GHG emissions, energy efficiency improvement potential, associated reductions in air pollutants, and the resulting global temperature impacts within China's cooling sector under various mitigation scenarios. The findings demonstrate that integrating refrigerant substitution with energy efficiency improvements yields the highest overall mitigation potential, substantially reducing both GHG and air pollutant emissions. Among the scenarios assessed, the Accelerated Transition to low-GWP refrigerants and enhanced Energy Efficiency (ATE) pathway exemplifies the effectiveness of such coordinated strategies. However, realizing these mitigation pathways requires addressing not only the technical potential at the equipment level but also the broader institutional, regulatory, and market challenges that influence real-world implementation.

The success of China's cooling-sector decarbonization trajectory largely hinges on the robustness of policy frameworks, the maturity of alternative low-GWP technologies, and the readiness of the market. Although our scenario analysis quantitatively illustrates future emissions under varying policy pathways, several institutional and systemic challenges must be addressed to translate these projections into reality. Key among these are the effective enforcement of regulatory measures, the risk of technological lock-in, and life-cycle management of refrigerants, each requiring targeted and detailed policy interventions. The variations in emission outcomes across scenarios are influenced not only by end-use demand but also by factors such as the availability, cost-effectiveness, and market uptake of alternative refrigerants; equipment turnover rates; and the strength of enforcement of minimum energy performance standards (MEPS). For instance, the substantial emission reductions projected under the ATE scenario hinge on the rapid and widespread deployment of high-efficiency cooling equipment and low-GWP refrigerants. Yet, the widespread adoption of promising refrigerant alternatives—particularly hydrofluoroolefins (HFOs)—continues to face commercialization hurdles, safety concerns⁴¹,

and cost barriers, especially in large-scale commercial chillers and specialized cold-chain equipment. In addition to these challenges, growing concerns have emerged regarding the environmental risks associated with atmospheric degradation of HFOs. Notably, HFO-1234yf degrades to trifluoroacetic acid (TFA) with near-complete conversion efficiency, far exceeding the TFA yields of conventional HFCs.

In China, several factors affect the near-term feasibility of the accelerated transition (ATE) pathway. Updated safety standards for mildly flammable refrigerants such as HFC-32 (A2L) and highly flammable hydrocarbon like HC-290 under the national standard GB/T 4706.32-202443 specify charge limits, ventilation, and monitoring requirements. While these revisions support pilot applications, wider industry adoption will require further adaptation. Domestic production capacity for low-GWP alternatives such as HFO-1234yf and HFO-1234ze remains limited, and supply-chain maturity and high upfront equipment cost pose additional challenges, particularly for large commercial systems that require extensive redesign and certification. Nevertheless, regulatory incentives, demonstration projects, and gradual localization of manufacturing are progressively reducing these barriers, suggesting that the ATE pathway could become technically and economically feasible in the medium term.

Moreover, Lifecycle Refrigerant Management (LRM) remains a critical yet inadequately developed component of China's climate mitigation strategy⁴². Recent data indicate that progress has been limited⁴³, with national recovery rates still below 3%⁴⁴. Existing regulations and practices for refrigerant recovery and destruction at the end-of-life stage are fragmented and lack consistent implementation across the country. As a result, a significant proportion of refrigerant emissions remains unaccounted for, thereby partially offsetting upstream mitigation gains achieved through refrigerant substitution. Strengthening LRM frameworks via enhanced regulatory mandates, targeted financial incentives, and improved recycling and destruction infrastructure presents a cost-effective opportunity to significantly augment climate benefits from the cooling sector.

While this study provides national-level estimates of reductions in air pollutants (SO₂, NO_x, and PM_{2.5}) associated with efficient and climate-friendly cooling, it does not include spatially resolved exposure or health-impact analysis due to data limitations. Future research could further integrate regional emission patterns and population exposure to explore the potential health-related co-benefits of mitigation. Nevertheless, the present results underscore the substantial potential of coordinated refrigerant transition and energy-efficiency improvement to deliver concurrent climate and air-quality benefits at the national policy level.

The indirect emission mitigation potential associated with energy efficiency improvement of cooling equipment varies significantly across regions, reflecting China's diverse power grid carbon intensities. Provinces heavily reliant on coal-fired generation—especially in central and western regions—produce disproportionately higher emissions per unit electricity consumed compared to regions with more renewable power penetration, such as coastal provinces⁴⁵. Consequently, identical efficiency improvements yield heterogeneous regional benefits in terms of climate and air quality outcomes. To maximize benefits, future energy efficiency policies must be tailored regionally, incorporating differentiated MEPS and integrated cooling-demand management into broader cross-sectoral strategies—such as multi-pollutant air-quality management frameworks and localized energy planning processes.

China's experience in the cooling sector has globally relevant implications that extend well beyond its borders. As the world's largest producer and consumer of cooling equipment—manufacturing approximately 85% of global room air conditioners (RACs), with half exported²¹—China's policy choices have far-reaching impacts on technology diffusion, supply chains, and regulatory standards. The integrated, multi-pronged approach highlighted in this study—combining the phasedown of HFCs, energy efficiency standards, and system-level governance—offers a scalable and replicable framework for other emerging economies facing rapid growth in cooling demand. In this context, China's transition provides a valuable

reference for developing countries seeking to expand access to cooling services while aligning with climate and sustainable development goals.

From a policy perspective, isolated measures are insufficient to achieve sustained and deep emission reductions within China's cooling sector. An integrated, multidimensional policy mix is essential, including: (1) expedited regulatory approval, standardization, and commercialization of low-GWP refrigerants with regularly updated replacement schedules; (2) progressively stringent MEPS, complemented by financial incentives and energy labeling initiatives to drive market adoption of high-efficiency equipment; and (3) a robust closed-loop refrigerant management framework encompassing production, use, servicing, recovery, and destruction phases.

In light of international climate policy benchmarks, the mitigation outcomes under the ATE scenario are well-aligned with recent global ambitions. Our results indicate that the four subsectors assessed in this study—RACs, MACs, CACs, and CCR equipment—can jointly achieve a 70% reduction in combined HFC and energy-related CO₂ emissions by 2050 under the ATE pathway. This indicates that, if China's domestic cooling sector follows the decarbonization trajectory outlined in ATE scenario, it would not only meet but surpass the COP28 target to reduce cooling-related GHG emissions by 68% by 2050 compared to 2022 levels¹⁹. It is worth noting, however, that our estimates focus primarily on domestically consumed equipment and do not comprehensively capture refrigerants used in exported units or in dispersed applications beyond the scope of our equipment-based inventory. Nonetheless, the ATE pathway represents a robust, sector-specific strategy, that is consistent with both national and global climate goals.

In conclusion, the cooling sector represents a strategically significant and manageable emission source at the nexus of climate change mitigation, energy system resilience, and public health protection. Achieving a resilient, low-carbon transition in China's cooling sector will require not only the deployment of advanced technologies but also adaptive institutional frameworks and innovative regulatory approaches. Under China's dual objectives of carbon neutrality and air quality enhancement, the sector provides a unique testbed for integrated mitigation strategies. By holistically aligning refrigerant transition, enhanced energy efficiency, and comprehensive life-cycle governance, policymakers can move beyond fragmented technological fixes towards a coherent, sustainable, and resilient cooling system.

Methods

This study employs the Refrigeration and Air Conditioning – Demand, Emission, and Cost (RAC-DEC) model, with modifications tailored to the scope of this analysis⁴⁶. The modeling framework consists of three core components: demand forecasting, emission estimation, and climate impact assessment. The technical structure of the model is presented in Fig. 5.

Demand modeling

We developed a bottom-up demand module to project the stock and sales of major cooling subsectors in China and to provide activity data for the emissions and electricity-use calculations. The model covers room air conditioners (RACs), mobile air conditioners (MACs), commercial air conditioners (CACs), and cold chain refrigeration (CCR). For each subsector, the evolution of in-use stock is described by a dynamic stock balance⁴⁷:

$$Stock_{i,t} = Stock_{i,t-1} + Sale_{i,t} - Disposal_{i,t} \quad (1)$$

Where $Stock_{i,t}$ denotes the in-use equipment stock in region i and year t ; $Sale$ the annual inflow of new units, and $Disposal$ the retired or scrap equipment.

Room air conditioners

RAC demand is modeled at the provincial level and differentiated between urban and rural households. We adopt a logistic diffusion framework⁴⁸, in which the penetration of RACs per household is driven by per-capita

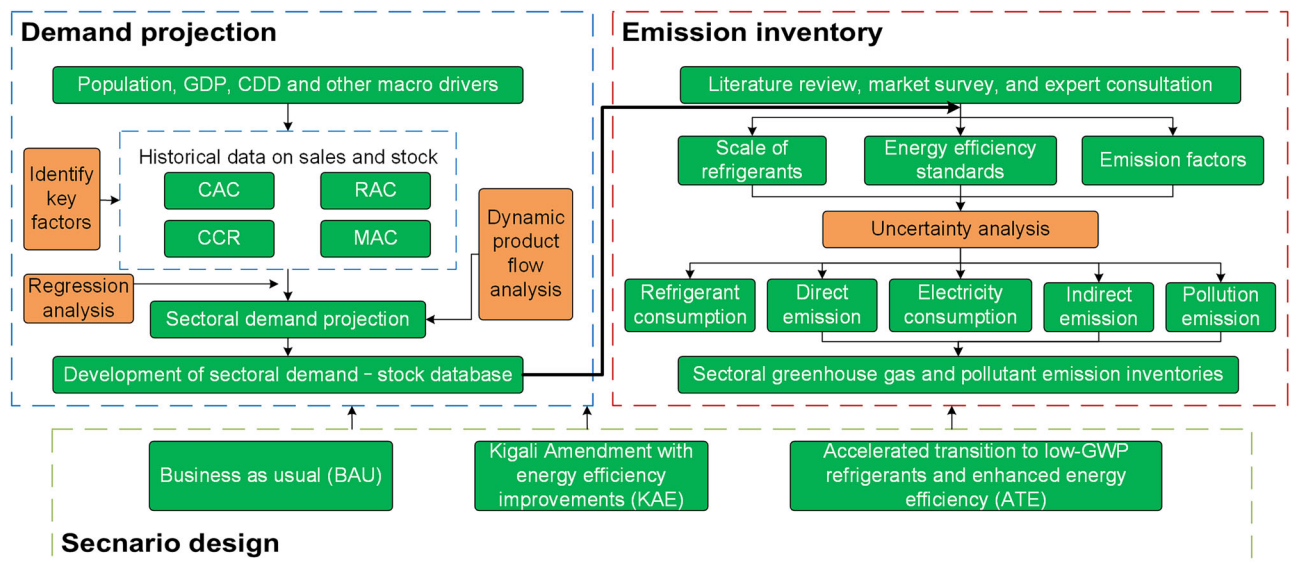


Fig. 5 | Schematic structure of the RAC-DEC modeling framework.

disposable income, urbanization, and climate conditions⁴⁹. The penetration rate Dif in province i and year t is given by:

$$Dif_{i,t} = \frac{\alpha_i \times (1 - 0.949 \times e^{-0.00187 \times CDD_i})}{1 + \gamma \times e^{\beta_1 \times I_{i,t} + \beta_2 \times U_{i,t}}} \quad (2)$$

Where I is per capita disposable income (RMB); U is the urbanization rate (%); α is the saturation level of RAC stocks influenced by local climatic conditions (units per household); γ and β are regression coefficients; and subscripts i and t indicate province and year.

$$\alpha_i = Max_i \times C_i = Max_i \times \left[1 - 0.949 \times e^{(-0.00187 \times CDD_i)} \right] \quad (3)$$

Where Max_i is the maximum affordable stock per household; for China we assume $Max_i = 2.67$ units per household⁵⁰. Historical penetration data are taken from the China Statistical Yearbook and harmonized across changes in statistical definitions. Population, household size, income, and urbanization are compiled from official statistical yearbooks and UN population projections; future trajectories are generated using a combination of gray forecasting and simple extrapolation methods. A complete list of variables, data sources, and fitted parameters for each province is provided in Supplementary Tables S1 and S2.

Mobile air conditioners

Vehicle-related cooling demand is represented through the stock of passenger cars, buses, and trucks equipped with MACs. An analysis of historical data from developed countries (1960–2018) confirms that most follow a Gompertz-like trajectory between vehicle ownership and GDP per capita (See Fig S1). Provincial vehicle ownership is projected using a Gompertz-type^{51–53} relationship between vehicles per capita and GDP per capita:

$$V_{i,t} = V_i^* \times e^{\alpha \times e^{\beta \times \frac{GDP_{i,t}}{Pop_{i,t}}}} \times Pop_{i,t} \quad (4)$$

Where $V_{i,t}$ is vehicle stock, V_i^* the saturation level, $GDP_{i,t}$ GDP, $Pop_{i,t}$ population, and α and β shape parameters. Historical vehicle and GDP data are obtained from the China Statistical Yearbook. To account for provinces that deviate from a standard Gompertz trajectory because of strong policy interventions or data irregularities, we apply differentiated modeling strategies summarized in Supplementary Table S3, combining Gompertz fits, trend extrapolation, and policy-based constraints. Assumptions on MAC

installation rates and the penetration of electric vehicles are aligned with national policy targets; details are given in Supplementary Information.

Commercial air conditioners

Demand for CAC systems is linked to the expansion of public and commercial building floor area²⁹. We first estimate total public building area as a function of GDP per capita:

$$S_t = a \times \frac{GDP_t}{Pop_t} + b \quad (5)$$

Where S_t is public building area, and a and b are regression coefficients derived from historical data (2000–2021). CAC equipment is grouped into unitary systems, variable refrigerant flow (VRF) systems, and water-cooled chillers (including screw and centrifugal types). For each equipment type, sales are assumed to scale with the annual growth rate of building area:

$$Sale_{i,t} = \frac{S_t - S_{t-1}}{S_{t-1}} \times Sale_{i,t-1} \quad (6)$$

Where $Sale_{i,t}$ is the sales of equipment type i . Historical stocks and sales by equipment class, as well as refrigerant charge per unit and market shares, are compiled from China IOL and related reports; sources and parameter values are summarized in Supplementary Fig S2.

Cold chain refrigeration systems

CCR demand is separated into refrigerated sales equipment (light commercial refrigeration) and cold storage. For refrigerated sales equipment, we use the value added of selected service sectors—wholesale and retail trade, accommodation and catering, and transport-related services—as the main driver⁵⁴:

$$Demand_t = k_i \times V_t + b_i \quad (7)$$

Where $Demand_t$ is the annual demand for equipment category i , and V_t is the combined value added of the relevant service sectors. For cold storage, total storage capacity is modeled as a function of real GDP:

$$Stocks_t = k'' \times GDP_t + b'' \quad (8)$$

Where $Stocks_t$ is national cold-storage capacity. Historical data on cold-chain capacity and value added are taken from China IOL; fitted

coefficients and assumed equipment classifications are given in Supplementary Figs S3 and S4.

Dynamic product flow analysis

For all subsectors, we apply a dynamic product flow (cohort) approach to link annual sales to stocks and retirements⁴⁷. Equipment lifetimes are represented by Weibull distributions, so that the fraction of a sales cohort retired at age x in year t follows

$$f_t(x) = F_t(x + 1) - F_t(x) \quad (9)$$

$$F_x = 1 - e^{-\left(\frac{x}{\lambda}\right)^k} \quad (10)$$

where $F(x)$ is the cumulative distribution function, λ the scale parameter, and k the shape parameter. Average lifetimes and the corresponding Weibull parameters for each subsector are taken from technical standards and previous studies^{55–58}, and are summarized in Supplementary Table S4 and Fig S5. For subsectors with sparse historical sales data, simplified retirement profiles consistent with expected service lives are used. The analysis is conducted primarily at the national level, given that data for CAC and CCR sectors are available only in aggregated form. For RAC and MAC, provincial-level data are used internally, but results are presented as national totals to ensure consistency across subsectors and facilitate comparison of mitigation scenarios.

The input datasets used in the demand modeling are available on Zenodo (<https://doi.org/10.5281/zenodo.17514280>).

Emission inventory

Emission estimates follow a bottom-up, activity-based approach that combines equipment activity levels with emission factors, adjusted for control measures. The general formula is:

$$E_{i,j,t} = AD_{i,j,t} \times EF_{i,j,t} \times (1 - R_t) \quad (11)$$

where $E_{i,j,t}$ represents the emissions of pollutant j in region i and year t (kg), AD denotes the activity level (e.g., equipment stock, refrigerant charge), EF is the emission factor (%), R is the emission reduction efficiency of control technologies (%).

Direct refrigerant emissions follow the 2006 IPCC Guidelines⁵⁹ and 2019 Refinement (Method 2a)⁶⁰, applying a stock–flow model that includes emissions from initial charging, operation, servicing, and end-of-life disposal. The full set of equations is provided in Supplementary Equations S1–S7. Refrigerant consumption, bank evolution, and retirement are computed using cohort-based stock modeling and Weibull lifetime distributions. For refrigerant GWP, this study adopts the 100-year GWP values from the IPCC Fourth Assessment Report (AR4)⁶¹.

Indirect emissions are based on equipment electricity consumption, derived from rated power and equivalent operating hours, combined with national average carbon-intensity trajectories. The detailed calculation formulas are provided in Supplementary Equations S8–S11.

All refrigerant-specific parameters, emission factors, lifetime distributions, and efficiency-class assumptions for each subsector (RAC, MAC, CAC, CCR) are documented in Supplementary Tables S4–S8 and Fig. S6–S7.

Scenario designs

We model three scenarios to evaluate future refrigerant and energy-related emissions from China's cooling sector: a Business-as-Usual (BAU) pathway and two mitigation scenarios - Kigali Amendment with enhanced Energy Efficiency (KAE) and Accelerated Transition to low-GWP refrigerants and enhanced Energy Efficiency (ATE)—consistent with differing levels of refrigerant transition and energy-efficiency improvement. All subsectors comply with the Montreal Protocol HCFC phase-out schedule, with HCFC-22 use in new RAC equipment ending in 2025.

A subsector-specific summary of refrigerant and efficiency assumptions is provided in Supplementary Table S9.

Uncertainty analysis

Uncertainties in direct refrigerant emissions are quantified using a Monte Carlo framework embedded within the stock–flow model. Key emission-factor parameters (initial charging, operation, servicing, and end-of-life) are perturbed by $\pm 10\%$, while activity data (sales, stocks, and charge sizes) are perturbed by $\pm 5\%$. For RAC and MAC, demographic uncertainty is incorporated by sampling across the UN World Population Prospects high-, medium-, and low-fertility trajectories.

For each subsector and scenario, 1000 simulations are performed. Each run generates time series of refrigerant bank, servicing demand, and life-cycle emissions. The resulting distributions provide annual mean values, standard deviations, and 95% confidence intervals (mean ± 1.96 SD). All sampled parameters are retained for sensitivity and attribution analysis.

Climate impact assessment

We quantify the climate effects of CO₂ and HFC emissions using established impulse-response and metric-based approaches. For CO₂, we apply the near-linear relationship between global mean temperature rise and cumulative CO₂ emissions, represented by the Transient Climate Response to cumulative CO₂ Emissions (TCRE). Following the IPCC AR5, TCRE is treated as a normally distributed parameter (mean 0.45 °C per 1000 Gt CO₂, $\pm 1\sigma$ range), and temperature responses are reported as the mean value with its $\pm 1\sigma$ uncertainty band.

For HFCs, we employ impulse-response functions (IRFs) to describe atmospheric decay, radiative forcing, and temperature response. Species-specific lifetimes, radiative efficiencies, and climate-response parameters follow standard formulations from Joos et al. and IPCC assessments. Climate impacts are expressed using the Absolute Global Warming Potential (AGWP) and Absolute Global Temperature Change Potential (AGTP), obtained by convolving emission time series with their corresponding IRF-based kernels. Feedback-adjusted metrics (AGWP* and AGTP*) are also applied to account for climate–carbon feedbacks.

All equations, numerical parameters, radiative-efficiency values, and IRF coefficients used in these calculations are provided in the Supplementary Equations S12–S28 and Table S10–S11.

Data availability

The datasets generated and analyzed in this study are publicly available on Zenodo at <https://doi.org/10.5281/zenodo.17514280>. Additional data supporting the findings of this study are available from the corresponding author, Pengnan Jiang, upon reasonable request.

Received: 10 August 2025; Accepted: 2 December 2025;

Published online: 16 December 2025

References

1. Falchetta, G., Cian, E. D., Pavanello, F. & Wing, I. S. Inequalities in global residential cooling energy use to 2050. *Nat. Commun.* **15**, 7874 (2024).
2. Dong, Y., Coleman, M. & Miller, S. A. Greenhouse gas emissions from air conditioning and refrigeration service expansion in developing countries. *Annu. Rev. Environ. Resour.* **46**, 59–83 (2021).
3. Gow, O. et al. Mitigation of extreme heat and sustainable cooling. in *25th IIR International Congress of Refrigeration* (LSBU, 2019).
4. Rocha, A. D. et al. Unprivileged groups are less served by green cooling services in major European urban areas. *Nat. Cities* **1**, 424–435 (2024).
5. Romanello, M. et al. The 2021 report of the Lancet countdown on health and climate change: code red for a healthy future. *Lancet* **398**, 1619–1662 (2021).
6. Khosla, R. et al. Cooling for sustainable development. *Nat. Sustain.* **4**, 201–208 (2021).

7. International Energy Agency (IEA). *Data and Statistics*. <https://www.iea.org/data-and-statistics> (accessed 16 June 2025).
8. Green Cooling Initiative. *Global Greenhouse Gas Emissions from the RAC Sector*. <https://www.green-cooling-initiative.org> (accessed 16 June 2025).
9. Baha, M., Hammami, S. & Dupont, J.-L. The Role of Refrigeration in the Global Economy. 3rd edn, Technical Brief on Refrigeration Technologies No. 60. <https://doi.org/10.18462/iir.TechBrief.04.2025> (International Institute of Refrigeration (IIR), 2025).
10. Waite, M. et al. Global trends in urban electricity demands for cooling and heating. *Energy* **127**, 786–802 (2017).
11. Colelli, F. P., Emmerling, J., Marangoni, G., Mistry, M. N. & De Cian, E. Increased energy use for adaptation significantly impacts mitigation pathways. *Nat. Commun.* **13**, 4964 (2022).
12. International Energy Agency (IEA). Seasonal energy efficiency ratio of residential air conditioners in key cooling markets. <https://www.iea.org/data-and-statistics/charts/seasonal-energy-efficiency-ratio-of-residential-air-conditioners-in-key-cooling-markets-2018> (2018).
13. Dreyfus, G. et al. Assessment of Climate and Development Benefits of Efficient and Climate-Friendly Cooling. <https://www.ccacoalition.org/resources/assessment-climate-and-development-benefits-efficient-and-climate-friendly-cooling> (United Nations Environment Programme & Kigali Cooling Efficiency Program, 2020).
14. Hodnebrog, Ø et al. The effect of rapid adjustments to halocarbons and N₂O on radiative forcing. *npj Clim. Atmos. Sci.* **3**, 43 (2020).
15. WMO (the World Meteorological Organization). *Scientific Assessment of Ozone Depletion: 2022* (Geneva, 2023).
16. Velders, G. J. et al. Projections of hydrofluorocarbon (HFC) emissions and the resulting global warming based on recent trends in observed abundances and current policies. *Atmos. Chem. Phys.* **22**, 6087–6101 (2022).
17. Purohit, P., Borgford-Parnell, N., Klimont, Z. & Höglund-Isaksson, L. Achieving Paris climate goals calls for increasing ambition of the Kigali Amendment. *Nat. Clim. Change* **12**, 339–342 (2022).
18. Tan, T., Rennels, L. & Parthum, B. The social costs of hydrofluorocarbons and the benefits from their expedited phase-down. *Nat. Clim. Change* **14**, 55–60 (2024).
19. UNEP (United Nations Environment Programme). Global cooling watch 2023: keeping it chill how to meet cooling demand, while cutting emission. <https://www.unep.org/zh-hans/resources/2023nianquanqiujiangwenguancha> (2023).
20. Purohit, P. et al. Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons. *Atmos. Chem. Phys.* **20**, 11305–11327 (2020).
21. Jiang, P. et al. Exploring Synergistic GHG Emissions Mitigation Potential and Costs of Room Air Conditioners. *Environ. Sci. Technol.* **58**, 15359–15370 (2024).
22. China IOL. *2019 White Paper on the Development of China's Refrigeration and Air Conditioning Sector*. <http://www.chinaiol.com> (China IOL Industry Research Institute, 2020).
23. Staffell, I., Pfenninger, S. & Johnson, N. A global model of hourly space heating and cooling demand at multiple spatial scales. *Nat. Energy* **8**, 1328–1344 (2023).
24. Miranda, N. D. et al. Change in cooling degree days with global mean temperature rise increasing from 1.5 C to 2.0 C. *Nat. Sustain.* **6**, 1326–1330 (2023).
25. IEA (International Energy Agency). *The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning*. <https://www.iea.org/reports/the-future-of-cooling> (IEA, 2018).
26. The Japan Refrigeration and Air Conditioning Industry Association (JRACIA). Estimates of world air conditioner demand 2024. <https://www.jraia.or.jp> (JRACIA, 2024).
27. McCulloch, M. T., Winter, A., Sherman, C. E. & Trotter, J. A. 300 years of sclerosponge thermometry shows global warming has exceeded 1.5 C. *Nat. Clim. Change* **14**, 171–177 (2024).
28. Wang, X., Purohit, P., Höglund-Isaksson, L., Zhang, S. H. & Fang, H. Co-benefits of energy-efficient air conditioners in the residential building sector of China. *Environ. Sci. Technol.* **54**, 13217–13227 (2020).
29. Wang, X. & Purohit, P. Transitioning to low-GWP alternatives with enhanced energy efficiency in cooling non-residential buildings of China. *Mitig. Adapt. Strateg. Glob. Change* **27**, 45 (2022).
30. Hu, S., Yang, Z., Yan, D., Wang, B. & Jiang, Y. Emissions of F-gases from room air conditioners in China and scenarios to 2060. *Energy Build.* **299**, 113561 (2023).
31. Dong, Y., Miller, S. A. & Keoleian, G. A. Estimating the greenhouse gas emissions of cold chain infrastructure in China from 2021 to 2060. *Sustain. Prod. Consum.* **31**, 546–556 (2022).
32. Adam, B. et al. Emissions of HFC-23 do not reflect commitments made under the Kigali Amendment. *Commun. Earth Environ.* **5**, 783 (2024).
33. Collaborative Labeling and Appliance Standards Program (CLASP). *Mepsy Methodology: Model and Approach for Climate Impact Analysis*. <https://doi.org/10.70098/OUAN6240> (CLASP, 2025).
34. United Nations Environment Programme (UNEP). *Data Centre—China HFC consumption and emissions (ODP and CO₂-eq)*. <https://ozone.unep.org/countries/data>. (accessed 16 June 2025).
35. Bai, F. et al. Pathway and cost-benefit analysis to achieve China's zero hydrofluorocarbon emissions. *Environ. Sci. Technol.* **57**, 6474–6484 (2023).
36. Ministry of Ecology and Environment of the People's Republic of China. *China's National Implementation Plan for the Montreal Protocol on Substances that Deplete the Ozone Layer (2025–2030)*. https://www.mee.gov.cn/xxgk2018/xxgk/xxgk03/202504/t20250423_1117396.html (MEE, 2025).
37. International Energy Agency (IEA). *Energy Efficiency 2024*. <https://www.iea.org/reports/energy-efficiency-2024> (IEA, 2024).
38. National Development and Reform Commission (NDRC), Government of China. *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy*. https://en.ndrc.gov.cn/policies/202110/t20211024_1300725.html (NDRC, 2021).
39. National Development and Reform Commission (NDRC), Government of China. *Action plan for reaching carbon dioxide emissions peak before 2030*. https://en.ndrc.gov.cn/policies/202110/t20211027_1301020.html (NDRC, 2021).
40. Abhyankar, N. et al. Achieving an 80% carbon-free electricity system in China by 2035. *iScience* **25**, 105180 (2022).
41. Lindley, A., McCulloch, A. & Vink, T. Contribution of hydrofluorocarbons (HFCs) and hydrofluoro-olefins (HFOs) atmospheric breakdown products to acidification ("Acid Rain") in the EU at present and in the future. *Open J. Air Pollut.* **8**, 81–95 (2019).
42. Purohit, P. et al. The importance of lifecycle refrigerant management in climate and ozone protection. *Sustainability* **17**, 53 (2025).
43. Chen, Z. et al. Sustainable management of banked fluorocarbons as a cost-effective climate action. *Environ. Sci. Technol.* **59**, 16356–16367 (2025).
44. Shang, S. et al. Challenges and suggestions for the refrigerant recovery industrial chain in China. *Refrig. Air-Cond.* **1**, 1–14 (2025).
45. Liu, N., Ma, Z. & Kang, J. A regional analysis of carbon intensities of electricity generation in China. *Energy Econ.* **67**, 268–277 (2017).
46. Jiang, P. et al. Coordinating to promote refrigerant transition and energy efficiency improvement of room air conditioners in China: mitigation potential and costs. *J. Clean. Prod.* **382**, 134916 (2023).
47. Oguchi, M., Kameya, T., Yagi, S. & Urano, K. Product flow analysis of various consumer durables in Japan. *Resour. Conserv. Recycl.* **52**, 463–480 (2008).
48. McNeil, M. A. & Letschert, V. E. Modeling diffusion of electrical appliances in the residential sector. *Energy Build.* **42**, 783–790 (2010).

49. Shah, N. K., Wei, M., Letschert, V. & Phadke, A. A. Benefits of leapfrogging to super efficiency and low global warming potential refrigerants in room air conditioning. Technical Report, Lawrence Berkeley National Laboratory (LBNL), United States Department of Energy. <https://doi.org/10.2172/1235571> (LBNL, 2015).
50. Zeng, Y., Land, K. C., Gu, D. & Wang, Z. *Household and Living Arrangement Projections* (Springer Publisher, 2014).
51. Wu, T., Zhang, M. & Ou, X. Analysis of future vehicle energy demand in China based on a Gompertz function method and computable general equilibrium model. *Energies* **7**, 7454–7482 (2014).
52. Wu, T., Zhao, H. & Ou, X. Vehicle ownership analysis based on GDP per Capita in China: 1963–2050. *Sustainability* **6**, 4877–4899 (2014).
53. Xiang, X.-Y. et al. Scenario analysis of hydrofluorocarbons emission reduction in China's mobile air-conditioning sector. *Adv. Clim. Change Res.* **13**, 578–586 (2022).
54. McNeil, M. A., Letschert, V. E., de la Rue du Can, S. & Ke, J. Bottom-Up Energy Analysis System (BUENAS)—an international appliance efficiency policy tool. *Energy Effic.* **6**, 191–217 (2013).
55. Habuer, Nakatani, J. & Moriguchi, Y. Time-series product and substance flow analyses of end-of-life electrical and electronic equipment in China. *Waste Manag.* **34**, 489–497 (2014).
56. Zeng, X. L., Gong, R. Y., Chen, W. Q. & Li, J. H. Uncovering the recycling potential of “new” WEEE in China. *Environ. Sci. Technol.* **50**, 1347–1358 (2016).
57. Hao, H., Wang, H., Ouyang, M. & Cheng, F. Vehicle survival patterns in China. *Sci. China Technol. Sci.* **54**, 625–629 (2011).
58. Zhou, S., Teng, F. & Tong, Q. Mitigating sulfur hexafluoride (SF₆) emission from electrical equipment in China. *Sustainability* **10**, 2402 (2018).
59. IPCC (Intergovernmental Panel on Climate Change). *Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*. <https://www.ipcc.ch/publication/good-practice-guidance-and-uncertainty-management-in-national-greenhouse-gas-inventories/> (IPCC, 2006).
60. IPCC (Intergovernmental Panel on Climate Change). *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 3. Industrial Process and Product Use*. <https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/> (IPCC, 2019).
61. IPCC. Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Ch. 2.10.2, https://archive.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html, accessed March 16, 2025.

Acknowledgements

P.J. acknowledges funding from the Peking University–International Institute for Applied Systems Analysis (PKU-IIASA) Postdoctoral Fellowship. P.P. acknowledges support from the European Commission through the

EU-CHINA-BRIDGE project (Grant No. 101137971) under the HORIZON-CL5-2023-D1-02-01 program. P.J., Z.C., F.B., X.C.Z., X.Z., and J.H. acknowledge funding from the Energy Foundation Beijing Representative Office under the project Research on roadmap to global near-zero emissions of HFCs with China's contribution and its socioeconomic implications (G-2306-34867).

Author contributions

P.J. conceived the study and led the manuscript writing. P.J. drafted the initial version and coordinated all subsequent revisions based on feedback from P.P. and J.H. X.X., Z.C., and F.B. contributed to methodological discussions and provided valuable suggestions to refine the analysis. X.C.Z. and X.Z. contributed to improving the manuscript through editorial input and critical feedback. All authors contributed to the interpretation of the results and participated in the preparation and revision of the final manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41612-025-01289-1>.

Correspondence and requests for materials should be addressed to Pengnan Jiang or Jianxin Hu.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2025