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Improving the energy efficiency of room air conditioners in China: Costs and benefits

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HIGHLIGHTS

- Variable speed units provide cost-effective solution to improve efficiency.
- Fixed speed units are not economically competitive at higher efficiency ratings.
- New standard brings accumulative CO_2 reductions of 12.8% between 2019 and 2050.
- Accumulative bill saving is 2620 billion RMB between 2019 and 2050.
- Continuous revision of the new standard could more than double the overall impact.

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ABSTRACT

China is the world's largest consumer of room air conditioners, and it contributes about a quarter of global space cooling CO_2 emissions. We model the costs and benefits of recently proposed new room air conditioner minimum energy performance standards (MEPS) in China. Our results suggest that newly proposed MEPS brings accumulative CO_2 emissions reductions of 12.8% between 2019 and 2050, and accumulative bill saving of 2620 billion RMB to China's consumers. The benefits of the proposed MEPS decrease with longer MEPS revision intervals and increase with shorter intervals—indicating that the intervals should be balanced to maximize benefits while accommodating constraints due to air conditioner manufacturer design cycles. We also model potential nationwide benefits from higher MEPS. Across two increasingly aggressive MEPS scenarios, China's room air conditioner electricity consumption and CO_2 emissions in 2050 are both reduced by 15–53% compared to the proposed MEPS. The highest-efficiency scenario (reaching MEPS of annual performance factor 5.4 in 2025) provides the largest long-term national benefits. These results could inform development of a Chinese regulatory regime that effectively updates room air conditioner MEPS. Because China is the world's largest manufacturer of room air conditioners, the economic, energy, and emissions benefits resulting from higher Chinese MEPS could also have a global reach.

1. Introduction

Global urbanization, electrification, increasing standards of living and demand for comfort, and falling air conditioner (AC) prices are expected to substantially increase the direct emissions from AC refrigerants and the indirect emissions associated with AC energy use. The past decade witnessed a rapid increase in AC ownership, particularly in emerging economies. In 2016, ACs and electric fans accounted for about a fifth of total electricity used in buildings worldwide. In addition, cooling demand was roughly 10% of the total global electricity consumption in that year [1]. According to the International Energy Agency [1], worldwide energy demand from ACs is set to triple by 2050, with emissions rising to 2070 million metric tons of CO_2 ($MtCO_2$), from 1135 $MtCO_2$ in 2016. Coupled with growing hydrofluorocarbon (HFC) use in ACs, as a replacement for chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), emissions from AC systems—without further controls—could partially negate the climate benefits achieved under the Montreal Protocol [2].

Emerging economies likely will drive the growth of AC ownership in coming decades. Growth potential is very high in many of these countries because relatively small proportions of their large and growing populations currently own ACs, and increasing per-capita

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Nomenclature

Δmfc	total incremental manufacturing cost
Δrp	retail price
$age(t)$	age of the AC in year$t$
$APF(m)$	efficiency rating of the design combination$m$
$baselinepowerinput$	power requirement of the baseline room AC
$bs(m, t)$	savings on the electricity bill with design combination m in year$t$
CC	cooling capacity
$cost_m(i)$	incremental cost of component$i$
$cumulativebs(m, t)$	cumulative savings on the electricity bill with design combination m in year$t$
$discount$	consumer discount rate
EER	energy efficiency ratio
$es_m(i)$	percent energy savings gained from component$i$
$fprice$	electricity price at year$t$
m	design combination
$markup$	markup rate from manufacturing cost to user price
ns	net savings
$p(m)$	payback
$SEER$	seasonal energy efficiency rating
t	year
$t\_es(m)$	overall percent savings of the design combination m
$UEC(m)$	annual electricity consumption of the design combination$m$

Table 1
Room AC sales by region between 2011 and 2017 (in million units).
Source: ChinaIOL [3] for China, JRAIA [15] for other regions.

	2012	2013	2014	2015	2016	2017
China	99.8	128.5	126.9	107.4	117.5	140.0
Asia (excluding China)	20.3	21.4	21.7	21.8	23.3	24.7
Europe	6.3	6.1	4.9	4.7	5.4	5.8
North America	7.5	7.9	8.2	8.1	8.0	8.1
South America	6.6	7.1	7.4	6.6	5.8	6.1
Middle East	3.7	4.7	4.8	4.7	4.6	4.4
Africa	2.2	2.3	2.3	2.3	2.4	2.3
Oceania	0.8	0.8	0.9	0.9	0.9	1.1

incomes, rising urbanization, and greater demand for thermal comfort are expected to expand AC ownership and use [3,4]. For example, whereas about 90% of residential buildings in the United States and Japan had central or room ACs in 2011, in 2013 room AC market penetrations were only 3% in India, 6% in Indonesia, and 16% in Brazil [5,6,1]. IEA [1] predicts that about half of global cooling demand growth by 2050 will come from emerging economies, including China, India, and Indonesia. China has already become the world's largest consumer (and manufacturer) of ACs. In 2016, its market penetration of room ACs in urban households reached 124% (up from 5% in the mid-1990s), although rural penetration remained below 47% [7]. That same year, China owned 35% of the 1.6 billion units of global AC stock [1]. In 2017, Chinese consumers purchased 73% of the approximately 193 million room AC sold worldwide, [8], Table 1).[2] In addition, China manufactured 70% of the world's RACs in 2017 [9].

Consequently, China's energy use for space cooling has increased dramatically, growing from 6.6 TWh in 1990 to 450 TWh in 2016 [1]. Because most of China's power generation is from coal-fired power plants, it led the world in CO_2 emissions from space cooling in 2016, contributing about 28% of global space cooling emissions (Fig. 1). In 2015, total electricity demand from room ACs accounted for about 30% of the peak summer load in some large and medium-sized Chinese cities [4]. During the summer heatwave of 2017, cooling demand pushed China's electricity demand to record highs [10]. China's cooling demand is expected to continue growing. Its cooling energy use per person is still less than 20% of the value observed in the United States (U.S.) [1].

Although China has adopted more than 60 mandatory minimum energy performance standards (MEPS) since the late 1980s related to residential appliances and commercial equipment, including room ACs, some of its existing MEPS are outdated and not very stringent. Because its MEPS for fixed-speed-drive (FSD) and variable-speed-drive (VSD) room ACs were last revised in 2010 and 2013, respectively, these standards do not reflect the market-based efficiency improvements that have resulted from national subsidy programs [11]. In addition, in most climate regions VSD compressors enable an AC unit to respond to changes in cooling requirements, improving performance and reducing refrigerant flow rates compared to the performance and refrigerant flow of conventional ACs with FSD compressors that cycle on and off [12]. VSD products that make ACs highly efficient already dominate mature AC markets such as Australia, Europe, Japan, and the U.S., and have rapidly increasing shares in emerging economies such as India [13].

Having two separate standards for FSD and VSD room ACs with much lower MEPS requirement for FSD enables inefficient FSD ACs to remain in the market. In recent years, China has been working on updating its room AC efficiency metrics and MEPS so that FSD and VSD ACs are covered under a single harmonized standard for the first time. The revised standard is expected to be published by the end of 2019 and be effective by the middle of 2020.[3]

Various existing studies evaluate the energy savings, emissions reductions, and economic benefits related to energy-efficiency standards and improvements for ACs and other appliances. Mahlia et al. [14] predict the potential mitigation of emissions through room AC energy-efficiency standards in Malaysia. Kwong et al. [15] analyze the energy-savings potential and cost-effectiveness of radiant cooling systems in Malaysia. Grignon-Masse et al. [16] assess the environmental impacts of energy-efficient European ACs using a lifecycle analysis approach. Rosas-Flores et al. [17] estimate the energy savings and CO_2 emissions reduction potential of urban and rural household appliances, including ACs, in Mexico. Borg and Kelly [18] focus on the electricity consumption and peak load impacts of appliance efficiency improvements in European households. Similarly, McNeil et al. [19] analyze the impact of energy-efficient appliances on Indonesia's peak load, finding that ACs will be the main driver of peak growth by 2025.

However, few studies discuss the impact of room AC efficiency standards and improvements in China. Those that do are now mostly outdated and underestimate the growth of AC ownership. Lin and Rosenquist [20] review Chinese AC standards and analyze the cost-effectiveness of the previously proposed standards in terms of the impact on energy savings, electric generation capacity, and CO_2 emissions reductions. Zhou et al. [21] estimate the energy-saving and CO_2-emission-reduction potential of China's appliance standards, including room AC standards, before 2010. Yu et al. [4] investigate the electricity savings and CO_2 emission reductions from room ACs under three different efficiency-improvement scenarios over the 2005–2025 period. Wu et al. [22] review the policy rules of energy-efficiency standards in China compared with standards in other countries, and they propose two methods to combine the global warming potential (GWP) of room AC refrigerants with energy-efficiency evaluation metrics.

Our paper investigates the impact of newly revised standard

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[2] Room AC sales accounted for 93% of total global AC sales in 2017 [8].

[3] Available here: http://www.cnis.gov.cn/gbzqyj/201903/t20190314_24782.shtml.

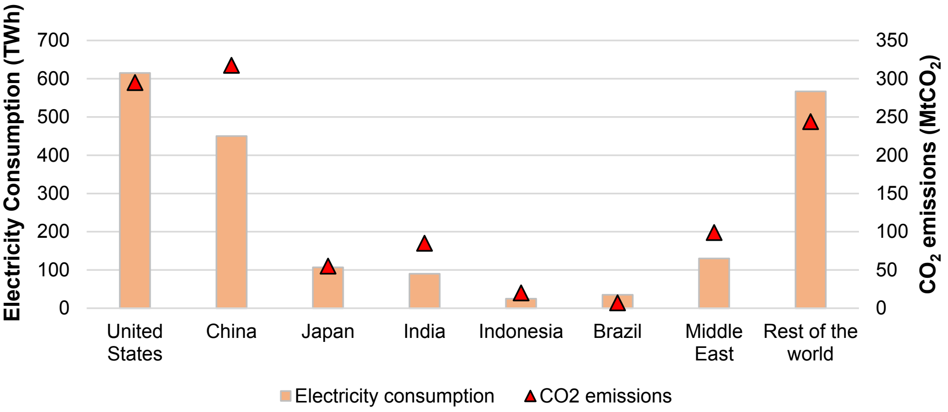

Fig. 1. Electricity consumption and CO$_2$ emissions due to cooling demand in 2016.
Source: IEA (2018).

Table 2
China's energy-efficiency label grade thresholds for FSD room ACs.
Source: Chinese Efficiency Standard GB 12021.3-2010 ("The minimum allowable value of the energy efficiency and energy efficiency grades for room ACs").

Type	Cooling Capacity (CC)	Grade 1	Grade 2	Grade 3
Split (EER)	CC ≤ 4.5 kW	3.60	3.40	3.20
	4.5 kW < CC ≤ 7.1 kW	3.50	3.30	3.10
	7.1 kW < CC ≤ 14.0 kW	3.40	3.20	3.00

Note: All ratings are in W/W.

Table 3
China's energy-efficiency label grade thresholds for VSD room ACs.

Type	Cooling Capacity (CC)	Grade 1	Grade 2	Grade 3
Split, Cooling Only (SEER)	CC ≤ 4.5 kW	5.40	5.00	4.30
	4.5 kW < CC ≤ 7.1 kW	5.10	4.40	3.90
	7.1 kW < CC ≤ 14.0 kW	4.70	4.00	3.50
Split, Reversible (APF)	CC ≤ 4.5 kW	4.50	4.00	3.50
	4.5 kW < CC ≤ 7.1 kW	4.00	3.50	3.30
	7.1 kW < CC ≤ 14.0 kW	3.70	3.30	3.10

Note: All ratings are in W/W.
Source: Chinese Efficiency Standard GB 21455-2013 [10] ("Minimum allowable values of the energy efficiency and energy efficiency grades for variable-speed room ACs").

(effective by middle of 2020); first providing estimates of the cost and benefits to the customer and second comparing the nationwide electricity demand and CO$_2$ emissions impact of the new standard with two other MEPS improvement scenarios. The analysis also focuses on the effect of different revision requirements in terms of stringency and timing and emphasizes the importance of proper revision targets and paces when establishing new standards. Because of China's dominant position in room AC manufacturing, its domestic room AC-efficiency policies would also have important global room AC cost, energy, and emissions implications.

The rest of the paper is organized as follows. Section 2 summarizes the Chinese room AC market and efficiency standards. Section 3 describes the methods and results of our high-efficiency AC cost-benefit analysis. Section 4 describes the methods and results of our national impact analysis relating Chinese room AC MEPS improvements to electricity-use and CO$_2$ emissions reductions. Section 5 summarizes the results and their implications for Chinese policy as well as areas for additional research.

2. Chinese room AC market and efficiency standards

Currently China categorizes room ACs into different types of FSD, VSD, and unitary (window-type) ACs, with different MEPS and corresponding mandatory energy-efficiency labeling thresholds set for each product category under different national standards [9]. The mandatory comparative energy label sets minimum efficiency requirements for three grades of efficiency, with Grade 3 set at the MEPS level and Grade 1 reserved for the most efficient products [23,24]. The share of unitary ACs is small in China: 0.3 million unitary units versus 43.2 million split-type (FSD and VSD) units [8]. Therefore, this analysis does not consider unitary/window-type ACs.

China evaluates the energy performance of FSD room ACs using Energy Efficiency Ratio (EER), defined as rated cooling capacity (CC) over rated cooling power consumption [23]. The Chinese efficiency metrics for VSD room ACs are a seasonal energy efficiency rating (SEER) for cooling-only products and an annual performance factor (APF) for reversible-type products (i.e., heat pumps) [24]. Table 2 presents China's energy-efficiency label grades for FSD room ACs (in EER). Table 3 presents the grades for VSD ACs (in SEER and APF).

The VSD share of room ACs sold in China increased from 18% in 2010 to 58% in 2018 [25]. Reversible-type products are dominant among VSD room ACs sold in the market. Fig. 2 shows the shares of FSD and VSD room AC sales between 2010 and 2018.

China's move toward VSD ACs follows a global trend driven by advances in information technology and semiconductor manufacturing, which have reduced VSD costs, and the adoption of seasonal efficiency metrics. In 2017, 100% of room ACs sold in almost all AC categories in North America, Europe, and Japan had VSDs [8].

Table 4 summarizes the newly proposed standards for cooling-only and reversible type products. The Phase I of the new standard imposes five grades covering both FSD and VSD room ACs, with Grade 5 set as the minimum threshold for FSD and Grade 3 as the minimum threshold for VSD. Once adopted and in effect, the Phase I requirements would be effective through 2021 and then revised in 2022, with Phase II requiring that Grade 3 become the minimum threshold for both room AC types.

3. Cost-benefit analysis

Economic analysis of advanced equipment has gained popularity, with increasing numbers of studies discussing the economics of energy efficiency, including studies on cooling systems. For example, Kwong et al. [15] performed a cost-benefit analysis of a radiant cooling system in Malaysia by comparing energy consumption and incremental cost between that system and a conventional variable-air-volume system. Similarly, Ozyogurtcu et al. [26] conducted an economic analysis of various heating, ventilation, and air conditioning (HVAC) modes for an operating room in Turkey. Özahioglu et al. [27] analyzed the economic

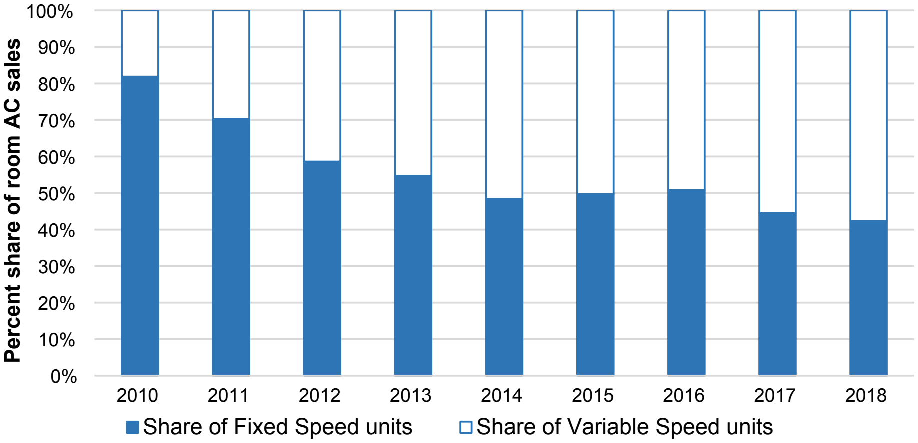

Fig. 2. Distribution of room AC sales in China between 2010 and 2018.
Source: ChinaIOL [25].

benefits of a variable-refrigerant-fluid (VRF) system compared to a conventional HVAC system in Turkey. Quan et al. [28] performed a cost-benefit analysis for variable operation of ventilation systems in subway stations. All of these studies used a test period, e.g., a year, to observe the performance of the efficient product compared to the existing technology, and calculate net benefits in this period. On the other hand, Shah et al. [3] considered various combinations of efficient components used in higher efficiency room ACs to estimate the total incremental cost and financial benefits of efficiency improvement to the AC owners. Shah et al.'s methodology is similar to those used in the U.S. and EU MEPS rulemaking process to estimate the incremental cost of efficiency improvement. This analysis follows the same approach to calculate the cost and benefits gained from using more efficient technologies in a room AC system.

3.1. Methods and main assumptions

The net benefits are calculated by summing the costs and benefits of each technology combination over the lifetime of the AC system and converting the result into net savings using a discount rate. Payback period for each combination is calculated using the annual electricity bill savings provided by that design combination relative to the baseline. Key analysis parameters include markup rates, hours of AC use, system lifetime, electricity price, annual growth of electricity price, and consumer discount rate. Our primary calculations are captured in the following equations.

Manufacturing cost and retail price:

The total incremental manufacturing cost (Δmfc) and retail price (Δrp) of the design combination m are calculated as follows:

$$\Delta mfc(m) = \sum_i cost_m(i) \tag{1}$$

$$\Delta rp(m) = \Delta mfc(m) * markup \tag{2}$$

where $cost_m(i)$ is the incremental cost of component i used in the design combination m compared to the baseline component. $markup$ represents the markup rate from manufacturing cost to user price.

Energy savings:

The overall percent savings of the design combination m, $t\_es(m)$, compared to the baseline model, is calculated as follows:

$$t\_es(m) = 1 - \prod_i (1 - es_m(i)) \tag{3}$$

where $es_m(i)$ is the percent energy savings gained from component i used in the design combination m compared to the baseline component.

Efficiency rating:

The efficiency rating (i.e., APF) of the design combination m is calculated as follows:

$$APF(m) = \frac{CC}{baseline\quad power\quad input * t\_es(m)} \tag{4}$$

where $APF(m)$ is the APF efficiency rating of the corresponding capacity and type of the design combination m, CC is the cooling capacity, and $baselinepowerinput$ is the power requirement of the baseline room AC.

Energy consumption:

The seasonal efficiency and annual energy consumption of a room AC can be determined by performance data and standard calculation methods in accordance with the Chinese national standard GB 21455-2013. Based on the data of 760 models collected in coordination with the Lawrence Berkeley National Laboratory (LBNL) International Database of Efficient Appliances (IDEA)[4], the annual electricity consumption of the design combination m, $UEC(m)$, is estimated by Eq. (5) for FSD and VSD room ACs.

$$UEC(m) = (-345.1 * \ln(APF(m)) + 691.7) * CCforFSD$$
$$, (-235.4 * \ln(APF(m)) + 566.67) * CCforVSD \tag{5}$$

Annual bill savings:

Annual bill savings from the advanced components used in the design combinations are calculated as follows:

$$bs(m, t) = (UEC(m) - UEC(baseline)) * \frac{fprice(t)}{(1 + discount)^{age(t)}} \tag{6}$$

where $bs(m, t)$ refers to the savings on the electricity bill with design combination m in year t, $fprice$ is electricity price at year t, $discount$ is the consumer discount rate, and $age(t)$ is the age of the AC in year t.

Net savings:

Net savings (ns)—the discounted value of benefits less costs over the lifetime of the AC system—are calculated as follows:

$$ns(m) = \sum_t bs(m, t) - \Delta rc(m) \tag{7}$$

Payback period:

Payback period, $p(m)$,—the length of time required to recover the

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[4] The IDEA automatically collects information at regular intervals from an array of online retailers and manufacturer websites cross-referenced the resulting models against the certification data from the China National Institute of Standardization (CNIS) appliance standards and labeling program to ensure that only models available on the market are listed (see [29] for more details about the database).

Table 4
China's new proposed MEPS grade thresholds for room ACs, effective middle of 2020.

Type	CC	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Split, Cooling Only (SEER)	CC ≤ 4.5 kW	5.80	5.40	5.00	3.90	3.70
	4.5 kW < CC ≤ 7.1 kW	5.50	5.10	4.40	3.80	3.60
	7.1 kW < CC ≤ 14.0 kW	5.20	4.70	4.00	3.70	3.50
Split, Reversible (APF)	CC ≤ 4.5 kW	5.00	4.50	4.00	3.50	3.30
	4.5 kW < CC ≤ 7.1 kW	4.50	4.00	3.50	3.30	3.20
	7.1 kW < CC ≤ 14.0 kW	4.20	3.70	3.30	3.20	3.10

Note: All grades are in W/W.
Source: CNIS [39].

cost of the investment—indicates when the economic benefits occur during the lifespan of each system. It is calculated as follows:

$$cumulative\ \ bs\ \ (m,\ t) = \sum_{t',t'<t} bs(m,\ t) \tag{8}$$

$$p(m){=}if\,(cumulative\ \ bs\ \ (m,\ t) \geq 0\ \ in\ \ t_0,\ \frac{\Delta rc(m)}{bs(m,\ t_0)},\ else\ \ t + \frac{cumulative\ \ bs\ \ (m,\ t-1)}{bs(m,\ t)} \tag{9}$$

3.1.1. Conversion of EER into SEER and APF

The non-seasonal EER that have been used for FSD units in China is not directly comparable to the APF, mainly because seasonal efficiency metrics such as SEER and APF take into account performance at part-load operation and outside temperature profiles that are used to aggregate steady-state and cyclic ratings. In addition, the APF is determined by total cooling and heating load over total cooling and hearing consumption, while the EER is by rated cooling capacity over rated power consumption. In this analysis, we convert EER into APF for FSD units to make the efficiencies of FSD and VSD technologies comparable. The relation between EER and SEER for FSD units (Eq. (12)) is taken directly from Wu et al. [30] and Wu and Ding [31]. The relation between EER and APF for FSD units (Eq. (13)) is estimated based on the same references. The SEER calculation in Eq. (12) is based on two set of data points: (1) actual performance data tested in full operation at 35 °C, and (2) performance data at 29 °C, calculated using the following equations. Calculation methods are commonly used to obtain performance data at 29 °C, but parameters used in the calculation may vary depending on the country (1.077 and 0.914 for China in this study).

$$Cooling\ \ full\ \ capacity\ \ at\ \ outdoor\ \ temperature\ \ 29\ \ ^{\circ}C = 1.077 \times Cooling\ \ full\ \ capacity\ \ at\ \ outdoor\ \ temperature\ \ 35\ \ ^{\circ}C \tag{10}$$

$$Cooling\ \ full\ \ power\ \ input\ \ at\ \ outdoor\ \ temperature\ \ 29\ \ ^{\circ}C = 0.914 \times Cooling\ \ full\ \ power\ \ input\ \ at\ \ outdoor\ \ temperature\ \ 35\ \ ^{\circ}C \tag{11}$$

Because these predetermined equations are used to estimate the performance at 29 °C, Wu et al. [30] and Wu and Ding [31] conclude that there is a linear relationship between EER and SEER, i.e., SEER = α × EER, with α being 1.012 for Chinese FSD units based on the GB 21455–2013 reference temperature bin hours.

$$SEER = 1.012 \times EER \tag{12}$$

In contrast, EER-APF conversion (Eq. (13)) can be varying with several parameters, particularly heating performance, e.g., heating efficiency (COP) and ratio of heating capacity over cooling capacity. Wu et al. [30] and Wu and Ding [31] provide a range of APF values corresponding to an EER data point in the Chinese standard. For example, depending on the heating performance, a room AC that has EER 3.52 can have an APF rating varying between 2.76 and 3.08. In our analysis, we use the median values of APF ranges shown in Wu et al. [30] and Wu and Ding [31] to develop a regression relationship between EER and APF for FSD units.

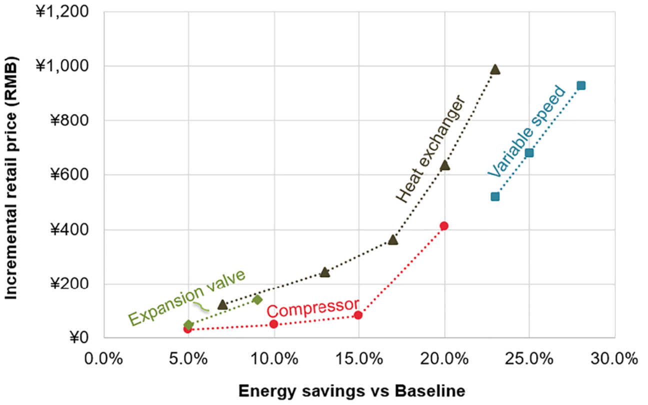

Fig. 3. Incremental retail price of efficient components for Chinese 3.5 kW CC (1.0 Refrigerant ton (RT)) mini-split room ACs. Note: The baseline compressor has a 2.9 EER rating. The large red dots from left to right on the compressor line represent 3.0, 3.2, 3.4, and 3.6 EER compressors, respectively. The blue squares from left to right on the variable speed line represent VSDs for an AC compressor, DC compressor, and DC compressor and fan, respectively. The brown triangles from left to right on the heat exchanger line represent heat exchanger improvements of 20%, 40%, 60%, 80%, and 100%, respectively. The green diamonds from left to right on the expansion valve line represent thermostatic and electronic expansion valves, respectively.

$$APF = 0.707 \times EER + 0.43 \tag{13}$$

3.1.2. Incremental prices of efficiency improvement

Several combinations of technologies can be used to improve the efficiency of room ACs. A cost curve for efficiency improvement is developed by creating 359 design combinations of efficient technologies and then estimating the lowest-cost combinations able to reach certain levels of efficiency. These technologies, both in the market and in development, tend to fall into one of four categories:

- Compressors
- Heat exchangers
- VSDs
- Expansion-valve technologies

We verify the simulated performance of the efficient technologies used in this study via actual performance data on efficient ACs in Riviere et al. [32]. The baseline room AC is based on the least efficient room AC in the Chinese market, an FSD room AC with an APF 2.7 rating and a retail price of ¥1927. Fig. 3 shows the electricity savings and incremental price for each efficiency component. Prices are in absolute values, and electricity efficiency improvements are shown in terms of the percent reduction in electricity demand compared to the baseline room AC. We developed the incremental manufacturing cost estimates

Table 5
Operational characteristics of ACs in China.

Parameter	Value	Unit	Source
Consumer discount rate	2.25	%	CIA [37]
Hours of use	1,569	hr/yr	China Efficiency Standard [24]
Lifetime years	12	yr	Khanna et al. [11]
Electricity price	0.55	¥/kWh	National residential average from LBNL [38]
Annual average increase rate of electricity price	1	%	Assumption based on expert input

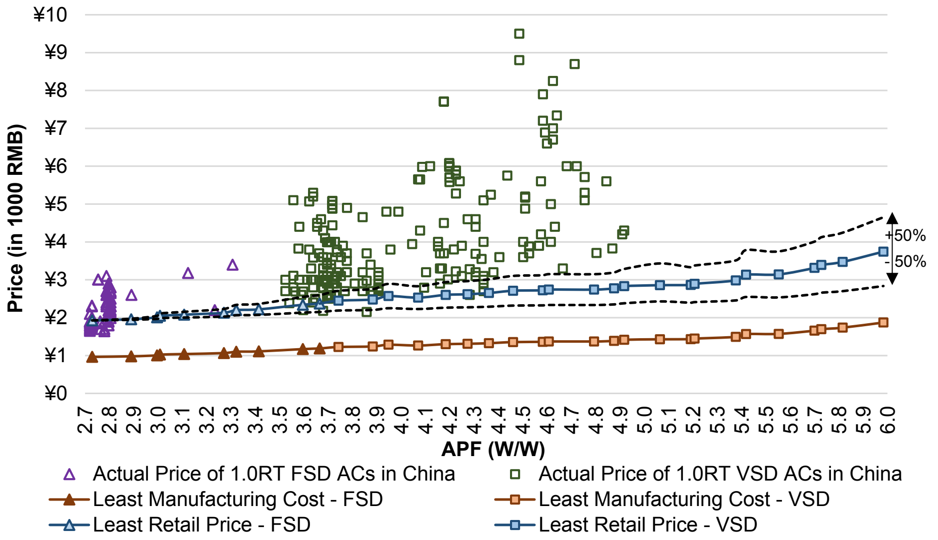

Fig. 4. Manufacturing cost and retail price increase per efficiency improvement of 3.5 kW CC (1.0-RT) mini-split room ACs in China. Note: The EER-APF conversion equation for FSD units used in this study (see Eq. (13)) is based on the median values of APF ranges shown in Wu et al. [30] and Wu and Ding [31]. The APF range for EER 3.2 (minimum requirement for FSD units) in these studies varies between 2.6 and 2.8, with a median value of APF 2.7.

of more efficient technologies in China using market research and interviews with appliance and component manufacturers in China. The incremental prices presented in Fig. 3 include a markup rate of 100% for shipping and installation, taxes, and manufacturer and retail price profit margins applied to ACs in China.

As explained at Eq. (3) (in Section 3.1.), individual electricity savings of components are multiplied when calculating the total electricity savings potential of a design combination. In addition, based on expert input from China room AC market, we only included the design combinations that provide less than or equal to APF 6.0.

3.1.3. *Other parameters*

Other parameters of the operational characteristics of ACs in China are summarized in Table 5. The markup rate on manufacturing cost is assumed to be 100%, based on calibration of the model with real market prices (see Section 3.1.2).

3.2. *Results*

Fig. 4 shows our modeled least manufacturing costs and retail prices for 3.5 kW CC ACs at efficiencies of 2.7–6.0 APF, with a ± 50% change in incremental cost. The −50% sensitivity values represent costs and prices that could decline owing to learning or economies of scale [33]. The +50% sensitivity values are used to test the robustness of our findings if the prices are higher than our estimates. Fig. 4 also presents actual retail prices of 3.5 kW CC FSD and VSD room ACs in China to validate our price predictions based on a 100% markup rate. Current market prices appear to reflect the bundling of AC features other than efficiency, because prices at the same efficiency level vary by over 100%. Even though our baseline room AC is based on the least efficient room AC, an FSD AC, on the current market, the least cost of efficiency improvement could be both FSD and VSD in the analysis. As shown in Fig. 4, FSD room ACs are the least cost option for efficiency improvement until APF 3.7 (triangles represent FSD), after which it is all VSD (squares represent VSD). Since the current official MEPS rating for VSD ACs is APF 3.5, there is no VSD ACs between APF 2.7 and 3.5. Thus, the results show that when improving efficiency of an APF 2.7 room AC, FSD room ACs could be economically better than VSD room ACs only between APF 3.5–3.7.

As can be seen, improving the baseline APF 2.7 to the ratings on the proposed MEPS from the lowest to the highest: APF 3.0 (cooling only FSD between 2019 and 2021), APF 3.3 (reversible FSD between 2019 and 2021), APF 4.0 (reversible VSD from 2019 and reversible FSD from 2022), and APF 4.4 (cooling only VSD from 2019) can be achieved at a price increase of about 6%, 14%, 31%, and 41%, respectively (relative to the baseline FSD room AC). Improving to APF 5.4, which is the efficiency level of the highest efficient model on the Chinese market (2.6 kW CC), can be achieved at a price increase of about 55%. However, if the baseline was a VSD room AC, improving the MEPS of a VSD AC from APF 3.5 (the current official MEPS for this type) to APF 4.0, 4.4, and 5.4 would result in a much lower incremental price than an FSD baseline. The prices of VSD room ACs with APF 4.0, 4.4, and 5.4 would be approximately 5%, 10%, and 24% higher compared to an APF 3.5 VSD room AC with a price of ¥2399. Because China's market for VSD room ACs is already mature for APF ratings of 3.5–5.0 (shown in Fig. 4), it would be much easier for VSD models to progress to higher APF ratings. Efforts to retool and redesign manufacturing lines would be technologically more complicated, thus, more expensive, for FSD room ACs. Therefore, FSD room ACs might spontaneously disappear from the market with MEPS ratings higher than APF 3.5–3.7 range. From this point of view, eliminating the relatively inefficient FSD room ACs from the market with the combined single MEPS rating of APF 4.0 in 2022 would be the biggest win of the proposed MEPS.

Note that, although the results in this section focus on 3.5 kW CC, i.e., 1.0-RT, room ACs (which make up the majority of the Chinese AC market), the trends likely will be the same, regardless of AC capacity.

Please also note that if we used the minimum or maximum values of APF ranges provided in Wu et al. [30] and Wu and Ding [31] for EER-APF conversion for FSD units (instead of median values), the difference on the results would be minimal. Since the conversion only impacts FSD

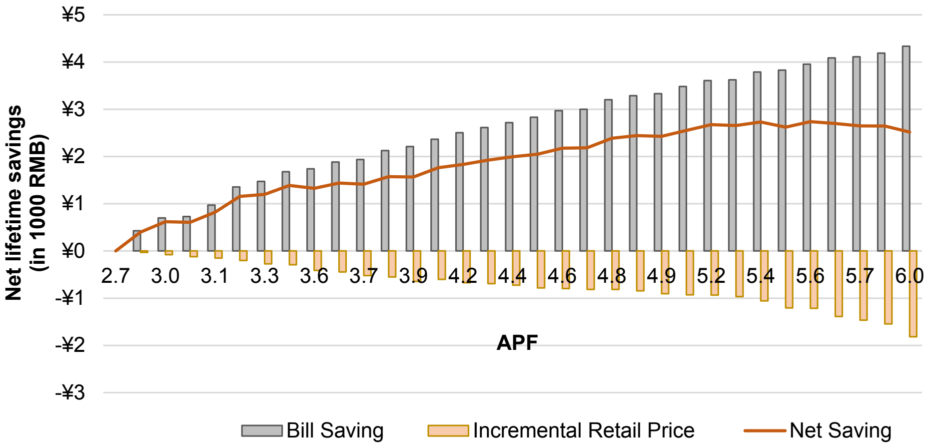

Fig. 5. Lifetime net savings for each design level of the least-cost curve.

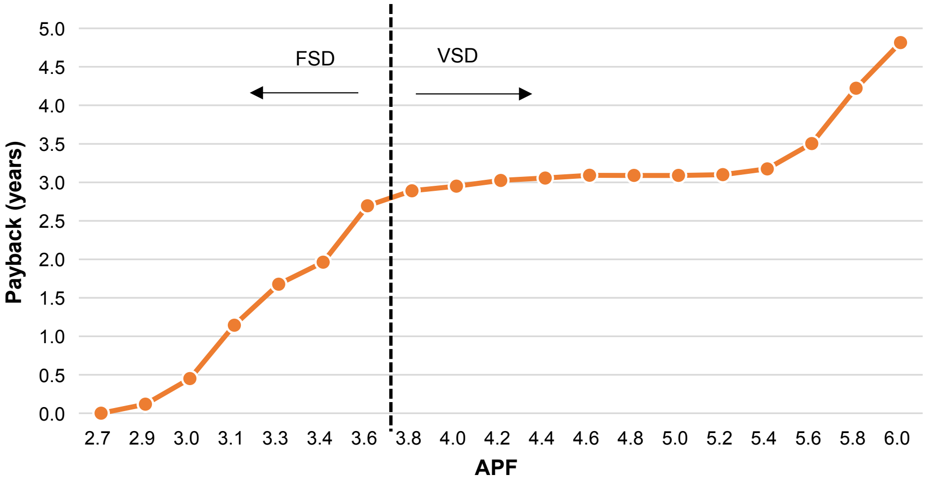

Fig. 6. Payback results for each design level of the least-cost curve.

units, the only change with the cost curve is the interval where FSD units are economically better than VSD units. The interval drops down from APF 3.5–3.7 to APF 3.5–3.6 with minimum values and increase to APF 3.5–3.8 with maximum values. These findings do not change the main conclusion of the study: FSD technology may spontaneously disappear from the market at higher MEPS ratings, which is set to APF 4.0 in the new proposed MEPS starting from 2022 onward.

Fig. 5 shows net customer savings over the full AC lifetime, based on accumulated electricity bill savings and the discounted initial AC price. Net savings increase with increasing efficiency until APF 5.4, after which net savings decline slightly. This result shows that increasing the stringency of MEPS up to APF 5.4 is likely to provide the largest consumer benefits.

Fig. 6 displays the payback periods for room ACs at each higher-efficiency design level, compared with the baseline APF 2.7 unit. The payback period increases significantly with increasing efficiency until APF 3.7; the line segment up to that point represents all FSD design options. In contrast, the change in payback period is minimal between APF 3.7 and 5.4, where all design options are VSD ACs. As mentioned above, if an APF 3.5 VSD AC were used as the baseline, the incremental price increases for higher-efficiency VSD ACs would be much lower, with corresponding payback periods of less than 0.5 years for efficiencies of APF 3.7–5.4. Clearly, increasing room AC efficiencies creates a larger financial burden when based on FSD models rather than VSD models.

Because payback periods are short and net lifetime savings increase up to a VSD room AC efficiency of APF 5.4, increasing MEPS for VSD room ACs to such a level likely would be financially beneficial for Chinese consumers. China's share of VSD room ACs already has been increasing rapidly (Fig. 2). Thus, establishing MEPS based on VSD room ACs with much higher APF ratings would not run counter to current market trends. Rather, it would accelerate the phase-out of relatively inefficient FSD room ACs.

4. National impact analysis

This section investigates the national level impact of the new room AC MEPS on short and long term electricity-use and CO_2 emissions reductions.

4.1. Scenarios

Based on the results of our cost-benefit analysis, in addition to the proposed MEPS, we create two additional scenarios to investigate the impacts of further improvement of the energy-efficiency standards: a medium-efficiency scenario (MES) and a high-efficiency scenario (HES). In the MES, current MEPS for both FSD and VSD room ACs are increased by 30%, starting in 2019. In the HES, MEPS is revised three times for all room AC types to APF 5.4 in 2025, which is the highest cost-effective efficiency rating based on our results on Section 3.2. In the MES and HES, corresponding payback periods are two and three years for FSD room ACs, respectively, and about 0.25 years for VSD room ACs. Table 6 details each scenario.

Table 6
Scenarios used in the national impact analysis.

	Baseline MEPS (APF)		Proposed MEPS (APF)		MES MEPS (APF)		HES MEPS (APF)	
CC	FSD	VSD	FSD	VSD	FSD	VSD	FSD	VSD
CC ≤ 4.5 kW	2.72	3.50	Refer to Table 4		3.54	4.55	MEPS is 5.4 APF in 2025 for FSD & VSD, with step improvement: (1) proposed MEPS from 2019 through 2021, (2) MES from 2022 through 2024.	
4.5 kW < CC ≤ 7.1 kW	2.64	3.30			3.43	4.29		
7.1 kW < CC ≤ 14.0 kW	2.55	3.10			3.32	4.03		

Note: All APF ratings are in W/W.

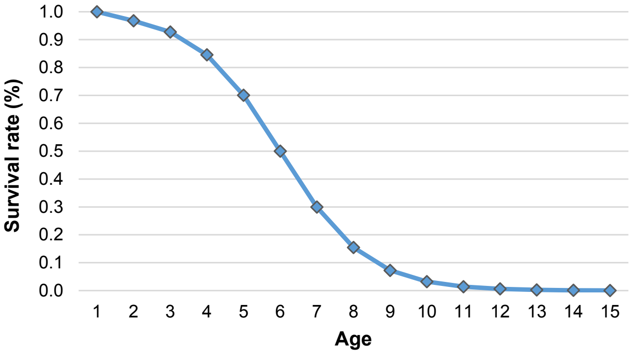

Fig. 7. Survival rate assumptions for Chinese ACs used in this study.

4.2. Methods and main assumptions

Our national impact analysis estimates annual mini-split room AC sales and stock, electricity consumption, CO_2 emissions. We first estimate new AC sales based on annual AC stock and scrappage of existing and new stock, considering the median AC lifetime and a growth parameter that determines how fast ACs are retired around the median lifetime. Annual AC stock growth (in number of ACs) in China from the 2019 baseline to 2050 is based on a bottom-up stock-accounting model that projects new AC demand using a saturation forecast based on macroeconomic drivers and historical experience in developed countries [11,34]. Based on China's recent rapid shift toward VSD ACs, we assume that FSD room AC sales will decline to 30% by 2025 and disappear by 2050 in the Baseline scenario. For the other scenarios, FSD room ACs are assumed to be phased-out from the market by 2022 due to high APF ratings set in the scenarios (see Section 3.2).

Scrappage function:

The literature around AC scrappage rates in China is very limited. We calculate China-specific scrappage rates through a logistic curve for new sales as follows:

$$survival_t = 1 - 1/\left(1 + e^{-\beta(t-t_0)}\right) \tag{14}$$

where t_0 is the median lifetime of the AC, t is the age in a given year, and β is a growth parameter that determines how fast the ACs are retired around t_0. We assume a median lifetime of 5 years for ACs in China and a β parameter of 0.85. Fig. 7 shows the AC survival curves used in this study.

Cumulative new sales:

Room AC stock, St_t, in a year are calculated as the sum of current new sales and prior-year sales of units that are still in service, as follows:

$$St_t = S_t + \sum_{u=1}^{t-1} S_u * survival_{t,u} \tag{15}$$

where S_t is the new sale in year t.

Total electricity consumption:

Total electricity consumption is calculated for each capacity to cover all room ACs in China, as follows:

$$P_t = St_t * k_t * UEC(m)_{FSD} + St_t * (1 - k_t)*UEC(m)_{vSD} \tag{16}$$

where P_t refers to the total power consumption of the room ACs in year t and k_t is the market share of FSD room ACs in year t. $UEC(m)$ is calculated with the same formula shown in Eq. (5) in Section 3.1.

Total CO_2 emissions:

Total CO_2 emissions in year t, $CO2_t$, are calculated as follows:

$$CO2_t = P_t \times CO_2 factor \tag{17}$$

where $CO_2 factor$ represents the CO_2 emissions intensity per kWh generated. We derive power-sector CO_2 emissions factors for China from Zhou et al. [35], with the factors decreasing over time based on recent market trends and assuming some fuel switching and growing shares of non-fossil generation (Fig. 8).

4.3. Results

Fig. 9 shows historical (2010–2018, from China IOL 2018) and projected (2019–2050) annual stock data and VSD room AC shares. We use the data from China IOL (2018) to calibrate the parameters β and t_0 in Eq. (12). Total room AC stock increases from about 0.46 billion units in 2018 to 1.36 billion units in 2050. In our efficiency scenarios, we assume that the higher MEPS apply to all new room ACs starting in 2019. Therefore, the stock with scenario MEPS does not differ among scenarios. However, the reduction in electricity consumption and CO_2 emissions vary owing to the different levels of MEPS improvements in each scenario. The share of new room ACs is 22% in 2019, so 22% of the total room AC stock is deployed under the scenario assumptions in that year. This share increases rapidly, reaching about 70% in 2022, 94% in 2025, and 99% in 2030.

Figs. 10 and 11 show China's room AC electricity consumption and CO_2 emissions in the baseline and efficiency scenarios between 2010 and 2050. In the baseline scenario, electricity consumption reaches 1526 TWh and CO_2 emissions reach 386 $MtCO_2$ in 2050. Compared with the baseline, proposed MEPS brings accumulative savings of 124 TWh (corresponds to 73 $MtCO_2$) between 2019 and 2021, and 4592 TWh (corresponds to 2136 $MtCO_2$) between 2021 and 2050. In addition, by 2021, cumulative bill savings to China's consumers from Phase I of the proposed MEPS is about 69 billion RMB. After Phase II revision of MEPS at 2022, this saving grows to 867 billion RMB by 2030 and 2620 billion RMB by 2050 (see Table 7).

Further improvement of MEPS in 2022 brings China to the levels comparable with current internationally-advanced minimum performance levels, and provides significant additional benefits. For example, if we assume that the new MEPS did not require a revision in 2022, China room ACs would emit 300 $MtCO_2$ and 581 $MtCO_2$ more CO_2 emissions by 2030 and 2050, respectively.

The MES almost doubles the accumulative electricity savings of the proposed MEPS to 9145 TWh while the HES provides significantly higher cumulative electricity savings −18,840 TWh (see Table 7). These findings indicate a significant savings potential from further improvement of MEPS. In 2050, annual electricity consumptions in the

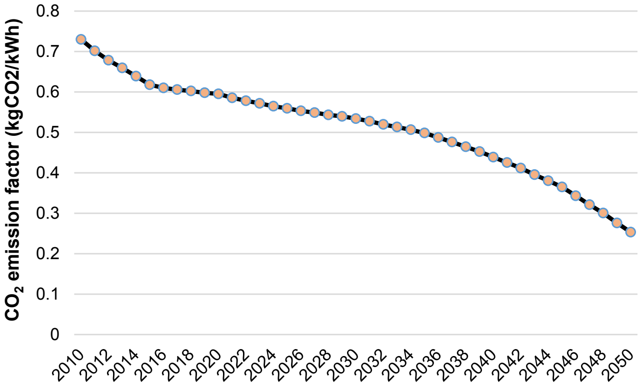

Fig. 8. CO_2 emission factors used in this study.

MES and HES are 15% and 53% lower than the proposed MEPS consumption.

4.4. Sensitivity to rebound effect and revision periods

Although our results suggest that more stringent MEPS can reduce electricity consumption and CO_2 emissions, the ultimate impact is uncertain for various reasons, including the rebound effect and uncertainty surrounding analysis parameters such as MEPS revision periods. In theory, improved efficiency reduces electricity bills and indirectly stimulates additional demand for AC use, which would, in turn, increase electricity consumption and emissions. As an example, Table 8 shows the impact of this rebound effect on electricity savings in 2050 for a 5% and 10% increase in AC use (i.e., in unit energy consumption per year). Electricity savings decrease in all scenarios. As can be seen, there are no savings in the proposed MEPS with a 10% rebound, but an increase compared to the Baseline.

Fig. 12 shows the change in electricity consumption in the proposed MEPS assuming different MEPS revision periods. If the MEPS are revised with one year delay in 2023 instead of 2022, cumulative CO_2 emissions between 2019 and 2050 increases by 16 $MtCO_2$, as indicated by the blue-shaded area in Fig. 12. In contrast, if the revision is done one year early in 2021, cumulative CO_2 emissions decrease by 21 $MtCO_2$, as indicated by the red-shaded area in Fig. 12.

Fig. 13 shows the additional reduction in electricity consumption in the new MEPS with a third revision period. If the proposed MEPS is improved 20%, which is similar to improvement rate between 2019 and 2022, in 3 years from 2022, and reach APF 4.8 by 2025, cumulative electricity savings between 2019 and 2050 increase by 2.5 times (4384 TWh), as indicated by the green-shaded area in Fig. 13. For comparison, China's total electricity consumption in 2017 was 6310 TWh. This result indicates the importance of continuous MEPS revision. Although MEPS should not be revised so frequently as to burden AC manufacturers inordinately, longer periods between revisions result in higher electricity consumption and CO_2 emissions in the short and medium terms. If the proposed MEPS is revised in 5 years from 2022, and reach APF 4.8 by 2027, increase in cumulative electricity savings would be 3.8% (276 TWh) lower compared to 2025 revision. In general, setting the revision periods at every 2 to 3 years can ease the burden on manufacturers' design cycles, which typically occur at the same interval [9].

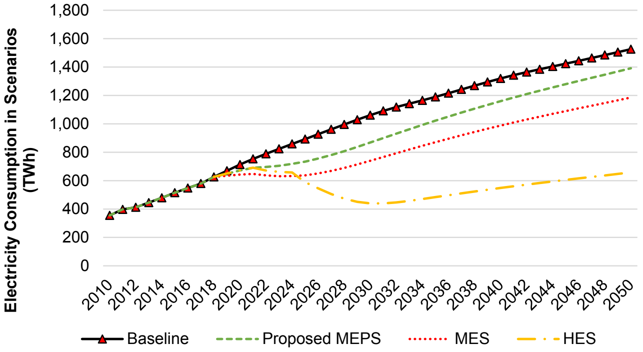

Fig. 10. China room AC electricity consumption in the baseline and scenarios.

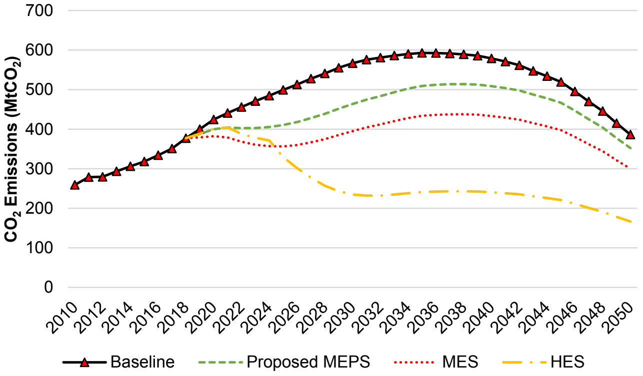

Fig. 11. China room AC CO_2 emissions in the baseline and scenarios.

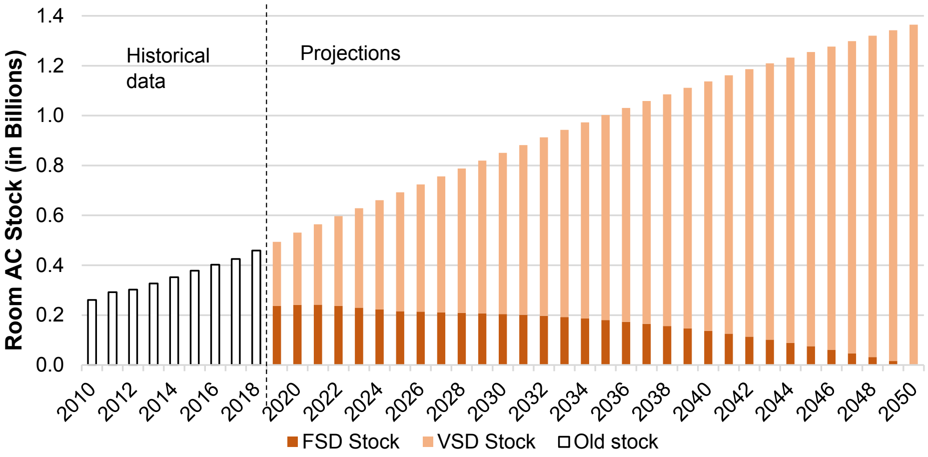

Fig. 9. Historical (2010–2018) and projected (2019–2050) annual room AC stock and VSD shares.

Table 7
Room AC annual electricity consumption, annual CO_2 emissions, and cumulative electricity and bill savings under the baseline and other scenarios in 2030 and 2050.

	2030				2050			
	Electricity consumption (TWh)	CO_2 Emission ($MtCO_2$)	Cumulative electricity saving (TWh)	Cumulative bill saving (10ˆ9 ¥)	Electricity consumption (TWh)	CO_2 Emission ($MtCO_2$)	Cumulative electricity saving (TWh)	Cumulative bill saving (10ˆ9 ¥)
Baseline	1061	567			1526	386		
MES	740	395	2549	1416	1185	300	9147	5081
HES	440	235	3464	1924	658	167	18,840	10,466
Proposed MEPS	868	464	1560	867	1392	352	4716	2620

Table 8
Sensitivity of electricity consumption to 5% and 10% AC-use rebound effect in 2050.

	No rebound		5% rebound		10% rebound	
	Electricity consumption (TWh)	Percent reduction	Electricity consumption (TWh)	Percent reduction	Electricity consumption (TWh)	Percent reduction
Baseline	1526		1526		1526	
Proposed MEPS	1392	9%	1461	4%	1531	−0.3%
MES	1185	22%	1245	18%	1304	15%
HES	658	57%	691	55%	724	53%

5. Conclusion

Our analysis indicates that China has substantial opportunity to improve its room AC efficiency using cost-effective technologies, particularly VSDs. Although some technologies considered in this paper may be currently unavailable in China, experiences in more advanced markets such as the European Union and Japan suggest that—with stringent MEPS, sufficient incentives, and robust regulatory programs such as labeling and procurement programs—high-efficiency ACs can be developed and deployed, providing significant CO_2 emissions reductions.

The key findings and implications of this study are summarized as:

(1) FSD room ACs are economically competitive only at MEPS up to APF 3.5–3.7, so FSD technology may spontaneously disappear from the market at higher MEPS ratings. At the same time, because payback periods are short and net lifetime savings increase up to a VSD room AC efficiency of APF 5.4, increasing MEPS for VSD room ACs to such a level likely would benefit Chinese consumers.
(2) Transitioning more rapidly toward VSD room ACs through higher MEPS would continue current Chinese and global trends in this direction and accelerate the phase-out of lower-efficiency FSD technologies. Transitioning China's remaining FSD manufacturing to VSD manufacturing would require few changes beyond adding capacity for semiconductor chip production.
(3) The newly revised MEPS that is expected to be in effect in middle of 2020 brings accumulative CO_2 emissions reductions of 12.8% between 2019 and 2050. Cumulative bill savings to China's consumers in the same period is 2620 billion RMB. In addition, according to the results, electricity consumption and CO_2 emissions in 2050 are both reduced by 15–53% compared to the proposed MEPS in our two higher efficiency scenarios.
(4) Continuous revision of the proposed MEPS with a third step by using similar improvement ratings could be more than doubling the overall impact in the 2019–2050 period in terms of electricity savings and CO_2 emissions reduction. However, its benefits decrease with longer MEPS revision intervals —indicating that the intervals should be balanced to maximize benefits while accommodating constraints due to AC manufacturer design cycles.

Overall, these results suggest that aggressive room AC MEPS could contribute significantly to helping China achieve its pledged Nationally Determined Contribution (NDC) goal of reaching peak CO_2 emissions by 2030 or earlier [36]. Toward that goal, the results could inform

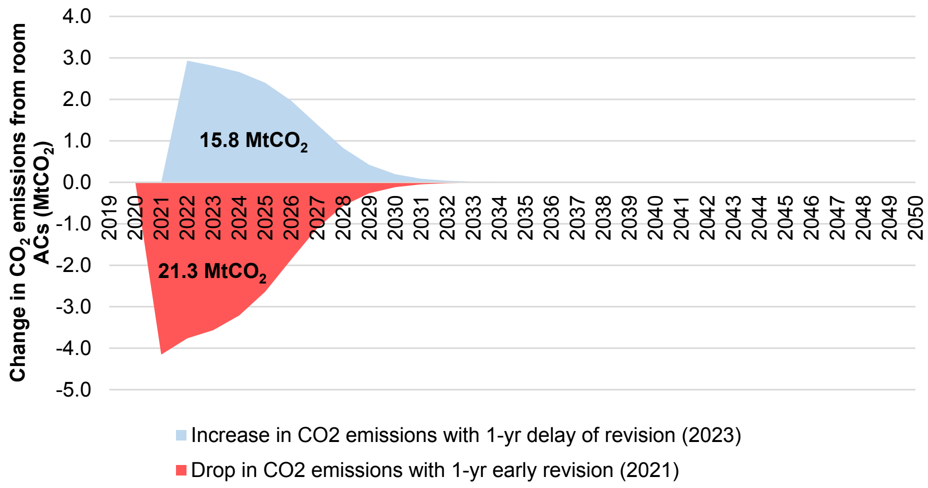

Fig. 12. Annual CO_2 emissions under different MEPS revision periods in the new MEPS.

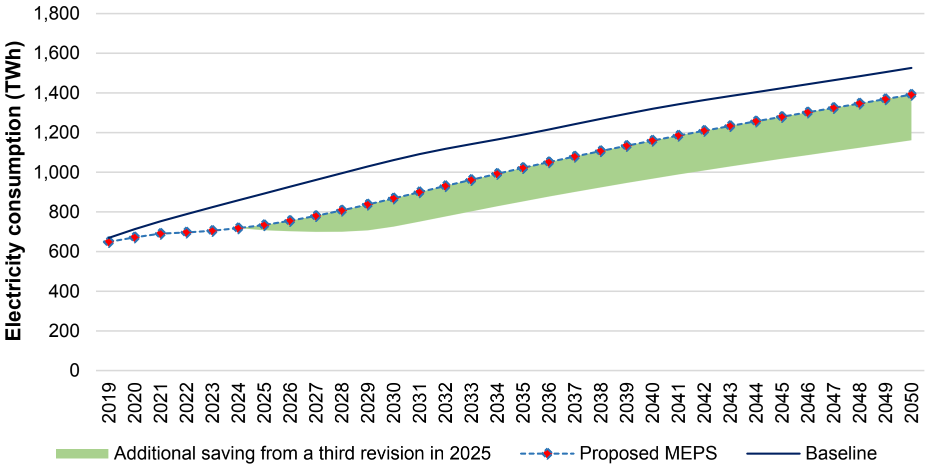

Fig. 13. Additional reduction in electricity consumption in the proposed MEPS with a third revision.

development of a Chinese regulatory regime that effectively updates room AC MEPS. Rapid development of such regulations for the post-2020 timeframe would give the AC industry sufficient lead time for research, development, and deployment of improved technologies. Because the industry is already subject to national commitments to transition to low-GWP refrigerants as part of the Montreal Protocol, aligning the implementation of AC efficiency standards with low-GWP criteria would be advantageous. Coordinating efforts will help minimize costs for consumers and manufacturers. In addition, because China manufactures over 70% of room ACs in the global market—and exports to areas with rapidly growing AC demand such as Southeast Asia—higher Chinese MEPS may produce widespread economic, energy, and emissions benefits.

The transition to higher-efficiency room ACs could also provide China with important air-quality and health benefits. In future research, we will extend our analysis to include emissions directly related to air quality, such as emissions of sulfur dioxide, nitrogen oxides, and particulate matter.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2019.114023.

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