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Authors

Park, Won Young
Shah, Nihar
Choi, Jun Young
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Lost in translation: Overcoming divergent seasonal performance metrics to strengthen air conditioner energy-efficiency policies

Won Young Park [a,*], Nihar Shah [a], Jun Young Choi [b], Hee Jeong Kang [c], Dae Hoon Kim [c], Amol Phadke [a]

[a] Energy Analysis and Environmental Impacts Division, Lawrence Berkeley National Laboratory, United States of America
[b] Korea Testing Laboratory, South Korea
[c] Korea Refrigeration and Air-conditioning Assessment Center, South Korea

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ABSTRACT

With increasing global uptake of variable-speed (inverter-driven) air conditioners (ACs), the globally uniform energy-efficiency ratio (EER) metric has given way to various region-specific part-load and seasonal performance AC metrics in many markets. As a result, policymakers around the world lack comparative data that might help them create more effective AC efficiency market-transformation programs. To help fill this gap, this paper explores relationships between the room AC efficiency performance metrics of different regions—including China, the European Union, India, Japan, South Korea, and the United States—using performance data for split room AC models. We use these interregional conversion relationships to estimate the performance of >6000 AC models, including reversible heat pumps, in efficiency metrics used in the six economies as well as the International Organization for Standardization (ISO) 16,358 metric. Our results suggest a way to identify the potential for improving AC efficiency policies in regional markets. The most efficient models sold in each region and worldwide typically are more efficient than the most efficient level recognized by regional energy standards and labeling programs. This information could help policymakers evaluate and improve their AC efficiency market-transformation programs to align with the globally best-available technology.

Introduction

Increasing incomes, electrification, and urbanization—as well as a warming world—are driving up global demand for room air conditioners (ACs), particularly in emerging economies with hot climates. The global stock of room AC units is expected to exceed 1.5 billion by 2030, up from 660 million units in 2015, and room AC energy consumption is expected to increase substantially (Shah, Wei, Letschert, & Phadke, 2015; United Nations Environment Programme, 2017). Improving the energy efficiency of room ACs will be critical to reducing their energy, peak load, and environmental impacts.

Energy-efficiency market-transformation programs for room ACs were initially implemented in the 1990s and early 2000s in many countries. At that time, most countries adopted the energy-efficiency ratio (EER) metric[1]—defined as the ratio of the total cooling capacity (CC) to the effective power input to the device at any given set of rating conditions—for rating AC performance based on International Organization for Standardization (ISO) Standard 5151, easily enabling comparison of performance across different markets and globally (International Energy Agency, 2011). In the early 2010s, the average efficiency of ACs across regions was estimated to be about 3.0–3.3 EER based on information from Australia, Canada, China, the European Union (EU), the Republic of Korea (hereafter called South Korea), and the United States (U.S.) (International Energy Agency, 2012).

AC manufacturers continue to research and develop advanced technologies to improve AC performance and reduce system costs. For example, highly efficient variable-speed-drive (VSD, also known as inverter-driven) products already dominate AC markets that demand energy efficiency, such as Europe, Japan, and the U.S. (Park, Shah, & Gerke, 2017). Variable-speed compressors enable an AC unit to respond to changes in cooling requirements, thus improving performance and reducing refrigerant flow rates compared with the performance and refrigerant flow of conventional ACs with fixed-speed-drive (FSD) compressors that cycle on and off (Shah, Phadke, & Waide, 2013).

Climate-specific weighting is used to calculate seasonal AC energy efficiency, which provides a more representative measure of performance than the traditional EER does. In the U.S., a seasonal energy-efficiency metric for ACs was developed in 1979 (Didion & Kelly, 1979). Since the mid-2000s, along with the trend of increasing penetration of VSD ACs,

* Corresponding author.
E-mail address: wypark@lbl.gov (W.Y. Park).

[1] EER is defined at the ISO T1 standard CC rating conditions for moderate climates at outdoor and indoor dry bulb temperatures of 35 °C and 27 °C. EER is also defined as the ratio of net CC or the rate of net heat removal (in Btu per hour) to the total rate of electrical energy input (in watts) of a cooling system under designated operating conditions. Although coefficient of performance (COP) is often used for cooling efficiency instead of EER, ISO 5151 defines COP as the ratio of the heating capacity to the effective power input to the device at any given set of rating conditions.

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region-specific seasonal energy-efficiency metrics have been designed or adopted to estimate AC performance under regional climatic conditions that affect the amount of time an AC operates at part or full load, and they are increasingly used as an alternative to the EER or COP to set standards and labeling (S&L) requirements for ACs and heat pumps.

However, because the seasonal energy efficiency of a commercially available AC is reported in region- and climate-specific metrics, it must be appropriately translated to other regions based on different energy performance due to differences across regions in efficiency metrics, climate, and operating conditions. Given the lack of publicly available test data, few studies explore the relationships among region-specific seasonal energy-efficiency values. This lack of comparative data hinders policymakers around the world who aim to improve AC efficiency market-transformation policies. Improved policies—such as minimum energy performance standards (MEPS), labeling, financial incentives, awards, and procurement programs—could accelerate the adoption of cost-competitive, highly efficient ACs to save energy, lower consumer electricity costs, and reduce greenhouse gas emissions.

To address the need for comparative information, this paper establishes relationships among the AC efficiency performance metrics of different regions—including China, the EU, India, Japan, South Korea, and the U.S.—using performance data for ductless split room AC models, with up-to-date regional standards. We also identify highly efficient room AC models in different regions and estimate their performance using the interregional efficiency conversion relationships. This analysis can be used to estimate the performance of AC models in a given region with another regional standard. The results highlight opportunities to realize significant efficiency improvement potential by aligning regional AC-efficiency policies with the capabilities of globally available high-efficiency ACs.

Literature review

Studies have compared the efficiency of available ACs and analyzed the differences between regional test methods and energy-efficiency metrics in several economies (International Energy Agency, 2011; International Energy Agency, 2012; Mahlia & Saidur, 2010; Shi, 2015; Wu, Xu, & Jiang, 2019). For example, in 2010, the International Energy Agency (IEA) 4E Mapping and Benchmarking study compared AC efficiency in terms of EER and identified efficiencies of the best and worst products for five economies: Australia, Canada, the EU, South Korea, and the U.S. (International Energy Agency, 2011; International Energy Agency, 2012). As in this study, the comparisons are typically based on EER, which does not fully capture performance at part-load operation or seasonal energy efficiency in each regional norm. Thus, EER values cannot be used directly to compare region- and season-specific efficiencies, mainly owing to different outside temperature profiles used for calculating seasonal efficiency as well as different ways of evaluating performance at part-load operation.

A few studies have explored the relationships among region-specific seasonal energy-efficiency values. A recent IEA study presented the seasonal energy efficiency of ACs available in various markets in regional efficiency metric terms (International Energy Agency, 2018). A Topten study identified energy-efficient ACs available in the EU and China, and it tested the performance of an AC sample under each regional test procedure (Michel, Bush, Nipkow, Brunner, & Bo, 2011). The Asia-Pacific Economic Cooperation (APEC) Energy Working Group investigated country-specific methods of calculating AC seasonal energy efficiency in APEC member countries—including Australia, New Zealand, China, Chinese Taipei, Japan, South Korea, the U.S., and Canada—and developed a seasonal energy-efficiency ratio (SEER) calculation program that provides different country-specific seasonal energy-efficiency values given test data inputs (Asia-Pacific Economic Cooperation (APEC), 2010). However, these studies (International Energy Agency, 2018; Michel et al., 2011; Asia-Pacific Economic Cooperation (APEC), 2010) did not provide mathematical conversion relationships, which can be used without detailed test data, among regional seasonal efficiency metrics. One recent study used a conversion factor (EER = SEER/1.2) for countries where seasonal efficiency data were available (GIZ (Internationale Zusammenarbeit GmbH), 2018). However, such an equation would vary by regional seasonal efficiency metrics because of the differences in test methods and ways of calculating a SEER. A comprehensive benchmarking study estimated linear regression equations for converting efficiency metrics between China, the EU, Japan, South Korea, and the U.S. to compare regional efficiency standards (Econoler et al., 2011). The study used test data on 52 ductless VSD AC models (the average and best-performing models available on the Japanese market from 1996 to 2006) to establish relationships across energy performance metrics used in the five regions. For converting the seasonal efficiency values of ductless split ACs from one region to another, the study considered performance data for two capacity stages (the rated CC stage and the intermediate CC stage)—measured under the previous Japanese Industrial Standards (JIS) C 9612:2005—with their respective cooling and electric power exhibiting the same variation with outdoor temperature. However, the linear regression relationships analyzed in (Econoler et al., 2011) were used for the regional MEPS comparison only. Regional efficiency metrics and standards used in (Econoler et al., 2011) must be updated with the latest versions. ISO 16358—with which the recent standards in Japan, India, and countries in Southeast Asia are consistent—was released in 2013 after the study was published. Our study provides updated region-specific seasonal energy-efficiency comparisons using the latest metrics and standards, including comparisons based on ISO 16358.

Methods and data

We analyze six economies—China, the EU, India, Japan, South Korea, and the U.S.—that account for about 70% of the global room AC market (Japan Refrigeration and Air Conditioning Industry Association (JRAIA), 2018). We use efficiency terms as they are used in the regional standards: SEER for China, the EU, India, and the U.S.; cooling seasonal performance factor (CSPF) for Japan and South Korea; and annual performance factor (APF) for heat pumps in China and Japan. Our analysis focuses on VSD ductless split ACs (including heat pumps), which are designed to improve energy performance at part-load operation, are typically among the more efficient ACs available on the global market, and have a growing market share in many countries. The share of VSD units in each market we analyze is already large, rapidly increasing, or both. See Appendix A for details on seasonal efficiency-related standards and test parameters for the select economies. The following subsections describe the methods and data we use to analyze the energy efficiency of these ACs across regions.

Estimating relationships between region-specific seasonal AC efficiency metrics

This study analyzes two sets of AC performance data. One set includes data from six room AC models measured according to ISO 16358 (Group A in Table 1). The seasonal efficiency calculation for VSD units is based on two sets of test data—measurement of performance (capacity and power input) at full- and half-capacity operations at an outdoor dry bulb temperature of 35 °C—and then performance at 29 °C is calculated by predetermined equations (see note *c* in Table A2). The seasonal efficiency calculation for FSD units is based on one set of test data—measurement of performance (capacity and power input) at full-capacity operation at an outdoor dry bulb temperature of 35 °C—and then performance at 29 °C is calculated by predetermined equations (see note *b* in Table A2). The second set of performance data analyzed in this study includes data from 24 VSD AC models measured according to Korean Standard (KS) C 9306 (Group B in Table 1). Table 1 summarizes the basic specifications of the select

Table 1
Basic specifications of the room AC models analyzed.

Group	A		B
Compressor type	FSD	VSD	VSD
Number of samples	2	4	24
Performance measured according to	ISO 16358:2013 (not including minimum capacity test)[a]		KS C 9306:2011 (including minimum capacity test)
Nominal CC (kW)	3.6	2.8–3.6	2.8–14.0
EER (W/W)	3.2	3.3–6.4	2.7–4.1
Ratio of heating capacity to CC	1.0–1.2	1.2–1.3	Not Available
COP (W/W)	2.6–4.5	3.9–6.2	Not Available

[a] See Appendix A for details on test parameters.

AC models. We calculate the country-specific seasonal efficiencies of the select AC models using their test data in China SEER, India SEER (ISEER), Japan CSPF, and Korea CSPF.

We also estimate part-load performance of the select VSD AC samples under the EU and U.S. test conditions to calculate EU SEER and U.S. SEER. To estimate the efficiency of the AC samples in EU SEER and U.S. SEER, we assume that performance (i.e., CC and power consumption) in the ISO and KS C full-load (100%) conditions at 35 °C is equivalent to that in the EU A and U.S. A_2 conditions, given the same indoor and outdoor temperature conditions. If the intermediate capacity of an AC (measured according to KS C 9306) in Group B does not fall in the half-capacity range (50% ± 5%), we estimate the performance at half capacity (50%). Performance at the other conditions is estimated as follows:

Step 1: Performance measured at full, half (or intermediate), and minimum capacity at 35 °C and 29 °C determines efficiency curves expressed as $y_t = a_t x_t^2 + b_t x_t + c_t$, where y_t is performance (i.e., EER) and x_t is capacity factor (%) at outdoor dry bulb temperature t. For example, one sample of the selected AC models produces the efficiency curves in Fig. 1.

Step 2: Based on the estimated efficiency curves at 35 °C and 29 °C for each AC sample, we estimate functions of the coefficients a_t, b_t, and c_t that determine the curves at other outdoor temperature points, expressed in $Y = d \times X + e$ where Y is coefficient a_t, b_t, or c_t and X is outdoor dry bulb temperature t.

Step 3: Based on the Step 2 results, we establish efficiency curves at different temperature points and estimate the performance required to calculate EU SEER and U.S. SEER. We calculate power consumption at outdoor temperature t using the relationship between capacity and EER:

$$\text{EER}(t) = \text{Capacity}(t)/\text{Power consumption}(t)$$

Step 4: We generate performance tables for each AC sample and select data points that are most relevant to parameters for calculating EU SEER and U.S. SEER, estimate AC performance in regional metrics, and finally establish regression relationships between regional seasonal efficiency metrics.

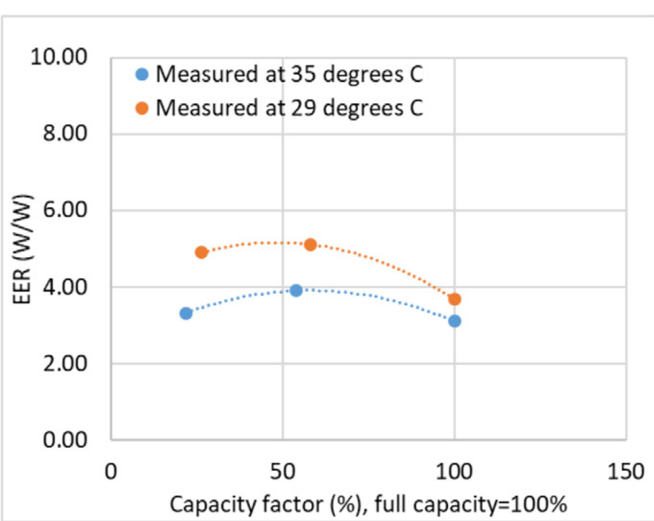

Fig. 1. Estimated efficiency curves for one AC sample.

Table 2 summarizes measured and estimated AC performance used in this analysis.

We tested one AC model commercially available in the EU in accordance with the ISO 16358 methods and estimated its performance under the EU and U.S. standards to validate this method. The estimated EU SEER of the sample is 5.72, which is 94% of the reported EU SEER of 6.10. The estimated U.S. SEER is 5.51, which is 107% of the measured U.S. SEER of 5.13 (Table 3).[2]

Although the AC performance estimate described above is focused on cooling efficiency, China and Japan use the APF metric, which combines cooling and heating efficiency to represent the performance of heat pumps widely available in these markets. When SEER and CSPF are converted into APF, we assume the products to be heat pumps (or reversible-type products). For the Group A models, we calculate China APF and Japan APF. For the Group B models, we use relationships between China SEER and China APF:

China APF = 0.7104 × China SEER +0.6403 ($R^2 = 0.812$, standard error = 0.135), estimated from the data from 92 reversible units with CC ≥ 7.1 kW

China APF = 0.8149 × China SEER +0.3052 ($R^2 = 0.907$, standard error = 0.125) estimated from the data from 486 reversible units with CC < 7.1 kW available in China (Table 4 describes the data set)

We also obtain relationships between Japan APF and Japan CSPF by solving the linear regression equations from (Econoler et al., 2011) as simultaneous equations: Japan APF = 0.799 × Japan CSPF +0.582.

Efficiency data for ACs available in six economies

This analysis focuses on interregional conversion of seasonal efficiency metrics for room ACs, because seasonal metrics capture real-world consumption more accurately and provide appropriate credit to key efficiency-improvement options such as VSDs. Since split ACs dominate the global room AC market and higher efficiency is driven by VSD ACs (Park et al., 2017), we focus on VSD split ACs when we convert all regional AC-efficiency values (collected from the selected regions) to each country-specific efficiency metric.

Our AC data are from several sources: 1) coordination with the Lawrence Berkeley National Laboratory (LBNL) International Database of Efficient Appliances (IDEA) initiative; 2) country- or region-specific databases such as those of the Energy Conservation Center Japan, the Korea Energy Agency, the Eurovent Certification, the Bureau of Energy Efficiency (BEE), and the Air-Conditioning, Heating, and Refrigeration Institute (AHRI); and 3) web searches. Table 4 summarizes the region-specific data collected for this analysis.

[2] We note that the estimated performance at part-load operation (e.g., U.S. Ev, B1, and F1 conditions and EU B, C, and D conditions) might not fully represent all performance settings (compressor frequency and fan speed) required under the test procedures for all AC units, possibly resulting in underestimated or overestimated SEERs.

Table 2
Measured and estimated AC performance used in calculations of ISO CSPF, EU SEER, and U.S. SEER (colored cells are most relevant for calculating EU SEER and U.S. SEER).

Capacity factor (%) (full capacity = 100%)	Minimum		Half (50% ± 5%) or Intermediate				Full
	Minimum[b]	21	47	50	Intermediate[a]	74	100
Outdoor dry bulb temperature (°C): 35	Measured or estimated (used for Korea min capacity)			Measured or estimated (used for ISO half capacity)			Measured (used for ISO full capacity, EU A, and U.S. A_2)
30					Estimated (used for U.S. E_v)	Estimated (used for EU B)	
29	Measured or estimated (used for Korea min capacity)			Measured or estimated (used for ISO half capacity)			Measured (used for ISO full capacity and U.S. B_2)
27.8	Estimated (used for U.S. B_1)						
25			Estimated (used for EU C)				
20		Estimated (used for EU D)					
19.4	Estimated (used for U.S. F_1)						

[a]The intermediate capacities of 24 AC models (Group B) range from 48%–80% of full capacity at 35 °C and 29 °C, varying by model.
[b]Minimum-load operation is defined as operation of the equipment and controls at minimum continuous capacity, varying by models and manufacturers. The minimum capacities of 24 AC models range from 9%–46% of full capacity at 35 °C and 29 °C (21% and 24% on average at 35 °C and 29 °C, respectively), varying by model.

Results

The following subsections present our results, translating AC efficiency into regional metrics and indicating the efficiency improvement potential from the most efficient ACs.

Relationships between region-specific seasonal AC efficiency metrics

We calculate the region-specific seasonal efficiency of the select AC models using their performance data and the methods described in Methods and data section, and then we establish regression relationships between regional seasonal efficiency metrics.

Fig. 2, Fig. 3, and Fig. 4 show the relationships between EER and ISO CSPF, China SEER and ISO CSPF, and China APF and ISO CSPF for the selected AC models. Appendix B shows all other relationships analyzed between regional metrics. All seasonal efficiency metrics are calculated by technology type, i.e., fixed- and variable-speed. Hence, the regression relationships between two seasonal efficiency metrics are established for each technology type as shown in Fig. 2, Fig. 3, and Fig. 4.

For FSD units, there is no large difference between the EER and CSPF values. Given that predetermined equations are used to estimate the performance at 29 °C, CSPF for FSD units results in a linear relationship with EER, i.e., CSPF = $\alpha \times$ EER (e.g., α~1.062 with the ISO reference temperature bin hours). The China SEER calculation for FSD units also results in a linear relationship with EER: SEER = $\beta \times$ EER (e.g., β ~1.012 with the GB 21455:2013 temperature bin hours) (Wu & Ding, 2019; Wu, Ren, Ding, & Cheng, 2016). The EER-APF conversions can vary by several parameters, including heating performance. For example, an AC that has EER 3.52 can have a China APF rating between 2.76 and 3.08 (Wu et al., 2016; Wu & Ding, 2019). Based on the median values of APF ranges shown in (Wu et al., 2016; Wu & Ding, 2019), we can obtain a relationship: China APF = $\gamma \times$ EER + δ (e.g., γ = 0.707 and δ = 0.43 with the GB 21455:2013 temperature bin hours).

For VSD units, the results (i.e., regression lines expressed in linear, exponential, or logarithmic equations) indicate that the correlation between regional efficiency values is higher when similar conditions are compared. For example, China APF (or SEER), ISEER, and Japan APF (or CSPF) correlate with high R-squared values, indicating that the fitted regression lines highly fit the data (see Tables B1–B4 in Appendix B). The differences in this case are primarily driven by the different temperature bin distributions used in the regional metrics.

The correlations between two metrics under different conditions (e.g., EU SEER vs. China APF or SEER, ISEER, or Japan APF or CSPF), have lower R-squared values. The difference is primarily driven by the different temperature bin distributions, different number of parameters considered, and different ways of including part-load performance as described in Appendix A. The linear regression relationships show that the possible difference between regional efficiency values tends to be larger as the efficiency gets higher. We also review the results from two other types of regression equations

Table 3
Reported/measured (under ISO standard) AC performance of one AC sample and its estimated performance in EU SEER and U.S. SEER.

EU SEER		U.S. SEER	
Reported by manufacturer	Estimated by authors based on ISO test results	Measured/calculated by authors	Estimated by authors based on ISO test results
6.10	5.72	5.13	5.51

Table 4
Summary of AC (and heat pump) data from selected economies.

Region	Number of models	Compressor type	Efficiency metric	Efficiency of the least efficient model	Average efficiency[a]	Efficiency of the most efficient model
China	578	VSD	China APF	3.11	3.92	5.45
EU	1268	VSD	EU SEER	4.60	6.66	10.50
India	599	VSD	ISEER	3.5	4.6	6.15
Japan	1308	VSD	Japan APF	4.50	5.86	7.90
South Korea	475	VSD	Korea CSPF	4.36	6.34	8.01
U.S.	2020	VSD	U.S. SEER	4.10	5.78	12.31

• China - We use a data set of about 580 VSD AC models (i.e., heat pumps) from LBNL IDEA. The IDEA data used in this study were collected for ACs from retail and manufacturer websites in China. The IDEA software combined the information from these sites and cross-referenced the resulting models against certification data from the national appliance S&L programs, such as the China National Institute of Standardization (CNIS) appliance S&L program for China (Gerke, McNeil, & Tu, 2017). We also reviewed data for energy-efficient models from Topten China, which provides information on the best-performing appliances and equipment, including room ACs, in that country.
• EU - We use a data set of about 1300 AC models listed in June 2018 on the Eurovent Certification website, which provides information on ACs and refrigeration products in Europe. We also reviewed data for energy-efficient models from Topten EU, which provides information on the best-performing appliances and equipment, including ACs, in that economy.
• India - We use a data set of about 600 VSD AC (cooling-only) models listed in 2018 on the BEE website. We also reviewed the Bijli Bachao website, which is an Indian equivalent of the Topten websites. The website provides information on the best-performing appliances and equipment, including room ACs, in India.
• Japan - We use a data set of about 1300 models (all heat pumps, registered from January 2018 to July 2019) from the Top Runner program database by the Energy Conservation Center Japan.
•South Korea - We use a data set of about 500 cooling-only products available in South Korea from the Korea Energy Agency database. These products were registered to the database between October 2018 and July 2019. The selected AC models meet CSPF 4.0 or greater (mostly qualified with Grades 1, 2, and 3), which makes them more efficient than the other levels (Grades 4 and 5).
• U.S. - Although split ACs in the U.S. are primarily ducted systems, we use efficiency data for ductless split ACs, because the global room AC market is dominated by this type of unit, known in the U.S. as mini-splits. We use a data set of about 2000 models (all heat pumps) available in the U.S. from the AHRI database.
[a] The average efficiency is calculated by dividing the sum of all models' efficiency by the total number of models in the data set, which could be different from sales-weighted market average efficiency. In some cases (EU, India, South Korea, and the U.S.) with data for high-efficiency products, it is likely to be higher than the average efficiency of all commercially available models.

(exponential and logarithmic, see Tables B3 and B4 in Appendix B). Although there appear to be no significant differences in R-squared values among these three types of regression equations, it is useful to consider them as predicting values in a range, particularly for higher efficiency values.

If the individual models exhibit a large scatter about a mean scaling relation, then selecting only the highest or lowest performers in one market is statistically guaranteed to yield converted values in another market that are biased (even if subtly biased) relative to the values one would measure using Market B's test procedure (on average). This is a statistical effect resulting from selecting items above a threshold in the presence of substantial intrinsic scatter and then applying a scaling relation. Although this effect will occur any time there is scatter and one chooses extreme values, in this case the effect is likely to be magnified by the fact that manufacturers likely design their high-efficiency units specifically to perform best under the regional test procedure. Hence, further analysis —including product testing—is needed to verify the calculated performance of the apparently highest-performing models in various regions.

Although regression relationships by technology type (i.e., FSD vs. VSD) can be established, this study attempts to derive one regression relationship to reduce the effect described above and address the complexity due to different technology types that can be perceived by non-technical users and policymakers. The blue dotted lines in Fig. 2, Fig. 3, and Fig. 4 show regression relationships combined for both FSD and VSD types in the Group A models in a sigmoid function:

$$y = d + \frac{a-d}{\left(1+\left(\frac{x}{c}\right)^{b}\right)}$$

For the relationship between China SEER (x) and ISO CSPF (y) in Fig. 3, the coefficients are a = 1.832, b = 3.125, c = 5.691, and d =

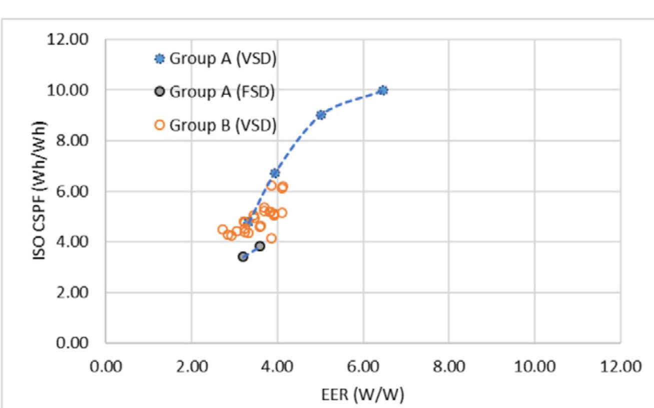

Fig. 2. Relationships between EER and ISO CSPF for selected ACs. The blue dotted line shows a regression relationship combined for both FSD and VSD types in the Group A models in a sigmoid function.

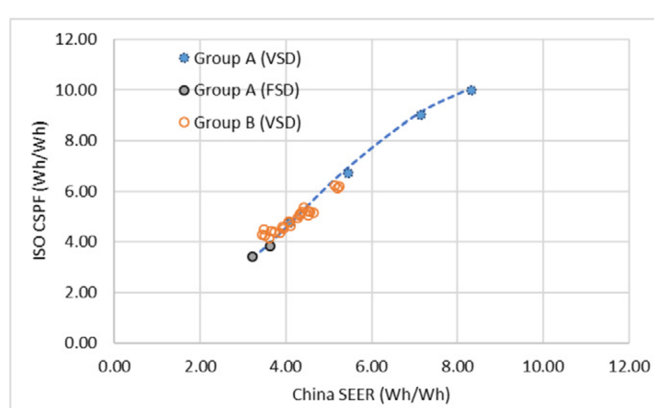

Fig. 3. Relationship between China SEER and ISO CSPF for selected ACs. The blue dotted line shows a regression relationship combined for both FSD and VSD types in the Group A models in a sigmoid function.

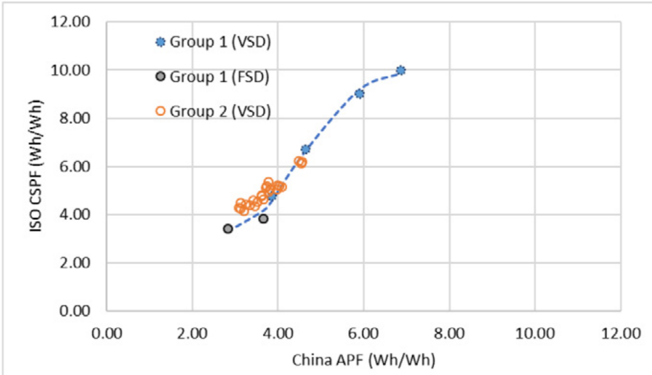

Fig. 4. Relationship between China APF and ISO CSPF for selected ACs. The blue dotted line shows a regression relationship combined for both FSD and VSD types in the Group A models in a sigmoid function.

12.483 with R-squared value = 0.991, *p*-value = 0.002, and standard error = 0.1321. All estimated equations for converting the seasonal efficiency of ACs from one region to another are summarized in Table B1 in Appendix B.

Table 5 shows the conversion results for seasonal energy efficiency. The regression relationships in Appendix B are applicable to the efficiencies of ACs available on the market (rather than hypothetical ACs with efficiencies outside the market range).

Policy insights from the most efficient ACs

Energy use or efficiency information is generally readily available for high-efficiency room ACs, yet policymakers often lack information about underlying technologies or efficiency improvement potential. Having information on energy-efficient and best-available room ACs in other regions could help policymakers improve their room AC efficiency programs to reflect technological improvements on the global market.

Here we provide such an interregional comparison based on the MEPS, the most stringent efficiency label, and the most efficient AC model in each region. Our analysis suggests the potential to improve AC efficiency in some regions based on commercially available technology. Specifically, the most efficient models sold in each region and worldwide typically are more efficient than the most efficient level recognized by regional energy S&L programs—suggesting the potential for significant energy savings if more stringent labeling or standards programs were implemented.

Table 5 and Fig. 5 show regional efficiency standards and those converted into the ISO CSPF metric. Because efficiency standards in some countries (e.g., China, Japan, and South Korea) vary by capacity, we select most stringent and least stringent classes that apply to the identified split AC models. Based on these estimates, South Korea's most stringent label is closest to the efficiency of the highest-efficiency models among these regions. The U.S. has the largest gap between its most stringent label and the efficiency of the highest-efficiency model in the region (partly because the relevant standard was developed for larger ducted split systems, which are more common in the U.S.). In all regions, the gap between the efficiencies of the highest-efficiency models and the MEPS is substantial.

This analysis uses regression equations to convert the efficiency of the identified most efficient AC models into ISO CSPF and other regional metrics, based on the regional metric/conditions under which the model was originally evaluated. These conversion results are only estimates, with uncertain precision—they are most useful for making broad initial comparisons. To validate the performance of an AC model under metrics/conditions other than those under which its performance was initially measured, detailed performance data must be collected under the new metrics/conditions.

Table 5
Interregional conversion of seasonal energy efficiency for split room ACs in Wh/Wh.

	Regional Efficiency Performance (X)			ISO CSPF predicted from X[a] [ISO APF predicted from X]		
Economy/efficiency metric	MEPS[b] (year effective from)	Most stringent class (year effective from)	Efficiency of best available product (year the model identified)	MEPS[b]	Most stringent class	Efficiency of best available product
India/ISEER	3.50 (2022)	5.50 (2022)	6.15 (2019)	3.79	7.04	7.97
Japan/Japan APF	4.5 (2010)	6.6 (2010)	7.9 (2019)	4.68 [4.49]	7.58 [6.54]	10.14 [7.80]
China/China SEER	5.00 (2022)	5.80 (2022)	6.03 (2019)	6.09	7.32	7.64
China/China APF	4.00 (2022)	5.00 (2022)	5.45 (2019)	5.17 [4.96]	7.59 [6.43]	8.54 [6.89]
South Korea/Korea CSPF	3.15 (2018)	10.66 (2018)	8.00 (2019)	3.44	10.06	8.18
EU/EU SEER	4.60 (2014)	8.50 (2014)	10.50 (2019)	4.48	8.82	11.05
U.S./U.S. SEER	4.10 (2015)	5.28 (2019)	12.31 (2019)	4.01	5.09	11.78

• India – The most stringent class and MEPS refer to 5-Star and 1-Star requirements. Those are expected to be revised to ISEER 3.50 and 5.50, respectively, effective between January 1, 2022, and December 31, 2024 (Bureau of Energy Efficiency, 2019).
• Japan – Japan's target standard values serve as MEPS and vary by type and capacity. For example, the target standard value for wall-mounted, non-ducted, free-dimension type ACs with CC ≤ 3.2 kW is APF 6.6, while that for wall-mounted, non-ducted ACs with 6.3 kW < CC ≤ 28.0 kW is APF 4.5. Here we use 4.5 as the lowest value and 6.6 as the highest value in the Japanese Top Runner program.
• China – At the time of this study, the China energy-efficiency standards for room ACs are expected to be revised by improving levels of requirements between 2020 and 2022 (Karali et al., 2019; UN Environment-Global Environment Facility, 2019b). Cooling-only products are required to meet SEER 5.00 (CC ≤ 4.5 kW), SEER 4.40 (4.5 kW < CC ≤ 7.1 kW), and SEER 4.00 (7.1 kW < CC ≤ 14 kW), and for Grade 1 SEER 5.80 (CC ≤ 4.5 kW), SEER 5.50 (4.5 kW < CC ≤ 7.1 kW), and SEER 5.20 (7.1 kW < CC ≤ 14 kW). We use 5.00 here as MEPS and 5.80 as the most stringent label. Reversible-type products are required to meet APF 4.00 (CC ≤ 4.5 kW), APF 3.50 (4.5 kW < CC ≤ 7.1 kW), and APF 3.30 (7.1 kW < CC ≤ 14 kW), and for Grade 1 APF 5.00 (CC ≤ 4.5 kW), APF 4.50 (4.5 kW < CC ≤ 7.1 kW), and APF 4.20 (7.1 kW < CC ≤ 14 kW). We use 4.00 here as MEPS and 5.00 as the most stringent label.
• South Korea – From October 1, 2018, onward, the Korea Energy Efficiency Standards and Labels require Grade 5 (MEPS), Grade 1, and Energy Frontier qualified ACs to meet CSPF 3.15, 8.20, and 10.66 or higher, respectively, for 4–10 kW split ACs, which constitute most of the ACs commercially available in South Korea.
• EU – From January 2014 onward, the Eco-design requirements (Reg. No 206/2012/EU) require ACs, except for single-duct and double-duct ACs, to meet SEER 4.14 for ACs with global warming potential (GWP) ≤ 150 for <6 kW and SEER 4.60 for GWP > 150 for <6 kW. We use 4.60 as MEPS here.
• U.S. – The most stringent efficiency class in the U.S. refers to the ENERGY STAR Most Efficient criteria (2019) for split type in residential central ACs. U.S. SEER is typically reported in BTU/h/W. To convert from the values shown here to the typical values reported in the U.S. market, multiply by 3.412.
[a] Calculations from equations in Table B1.
[b] Minimum energy performance standards

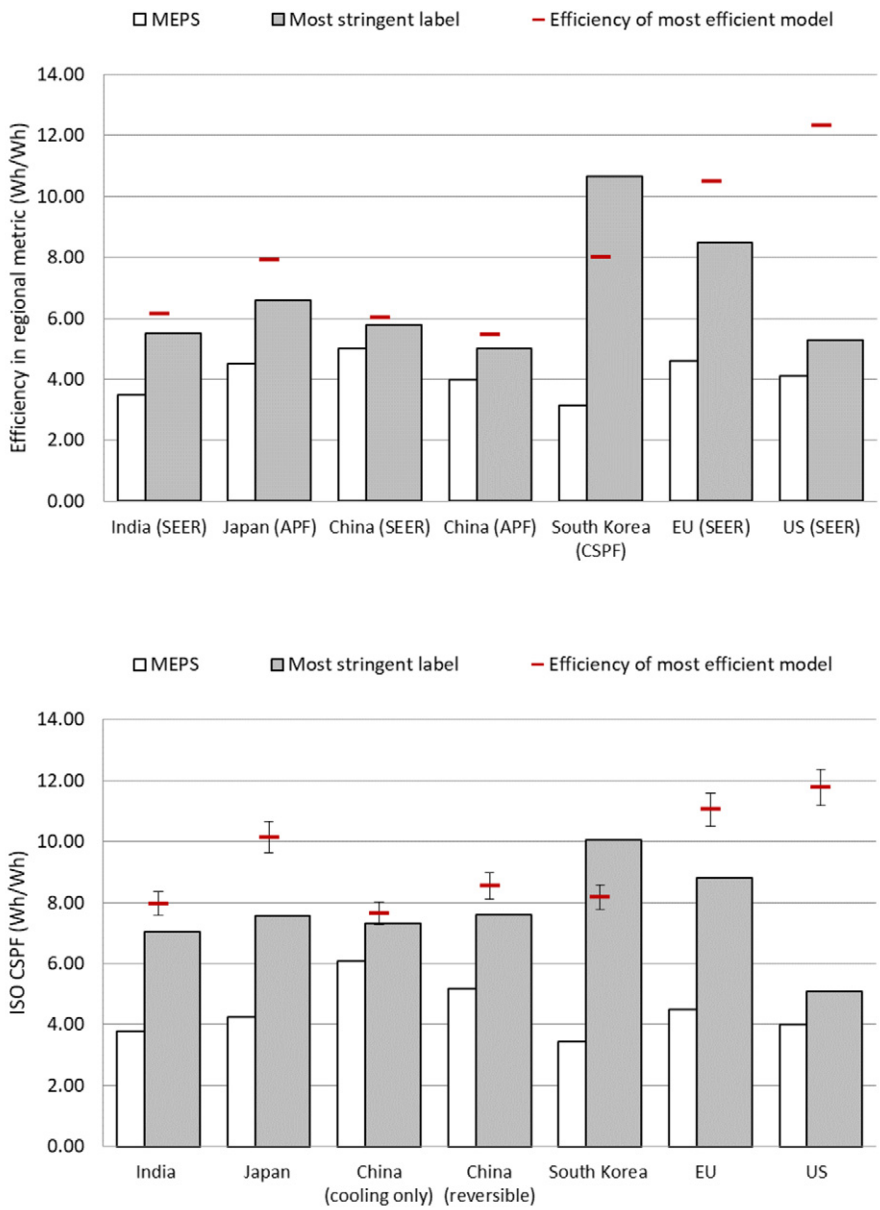

Fig. 5. Efficiency of most efficient models and regional S&L in regional metric (upper) and ISO CSPF (lower). Error bars represent ±5% range of the converted values.

Efficiency conversion results for commercially available ACs

Here we apply the scaling relations established above to compare commercially available AC efficiency distributions using one metric. Fig. 6 provides the efficiency conversion results for the 6248 VSD AC models collected from the six economies summarized in Table 4. The MEPS in place or expected to be implemented in these economies is assessed to have a wide range of efficiency levels in ISO CSPF, between about 3.4 and 6.1, varying by region as shown in Table 5.

As shown in Table 6, about 90% of the total VSD AC models converted in this analysis are estimated to meet ISO CSPF 4.5 (similar to the EU MEPS) or greater. About 40% of the AC models are estimated to meet ISO CSPF 6.1 (similar to the China 2022 MEPS for cooling-only products) or greater; this efficiency level can serve as a reference for regions that are considering setting energy-efficiency standards in a similar time frame (see (UN Environment-Global Environment Facility, 2019a; UN Environment-Global Environment Facility, 2019b) for potential implications). The most stringent class in place or expected to be implemented is also assessed to have a wide range of efficiency levels in ISO CSPF, between about 5.1 and 10.1, varying by region. Although the lower bound (ISO CSPF 5.1) of the most stringent class is estimated to be slightly less than the upper bound of the MEPS, the majority of most stringent classes (>ISO CSPF 7.0) is greater than all MEPS. The lower bound (ISO CSPF 5.1) is estimated to be met by 70% of the total AC models converted in this analysis, compared with 3.5% meeting at least ISO CSPF 8.8 (similar to the EU A+++ class) and 0.3% meeting at least ISO CSPF 10.1 (similar to the Korea Energy Frontier). In relation to the level of MEPS, some of these efficiency levels can be used as a reference for improving energy-efficiency labels or incentives in other regions as well as the select regions.

Conclusion and policy implications

Energy-efficiency test data for AC models in different regions can be used to estimate the performance of these models in any region- or

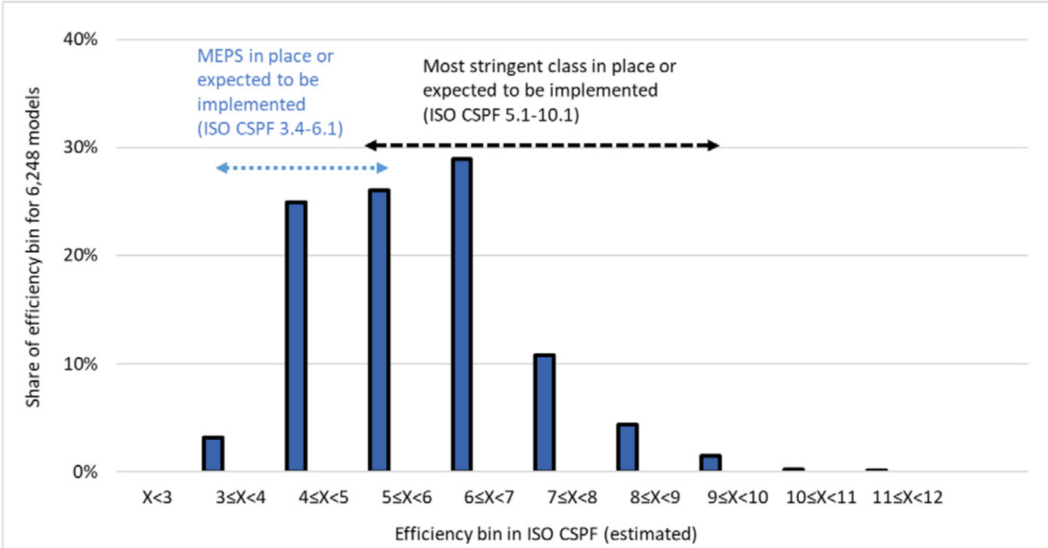

Fig. 6. Efficiency distribution of 6248 VSD AC models in ISO CSPF.

country-specific metric if all the required and optional test points are measured. The difference in seasonal efficiency metrics of ACs is primarily due to the outside temperature profiles used to aggregate steady-state and cyclic ratings into a seasonal efficiency value, as well as the ways of evaluating performance at part-load operation in each metric. The Chinese, Japanese, and Indian metrics give weight to full-and half-load performance. The Korean, EU, and U.S. metrics include minimum-load performance at low temperatures.

Because consumers and policymakers around the world lack such detailed technical data or comparative information, we establish relationships between the AC efficiency performance metrics of different regions—including China, the EU, India, Japan, South Korea, and the U.S.—using performance data for select split room AC models measured according to ISO 16358 or KS C 9306. Our interregional AC efficiency conversion in some cases provides conservative (i.e., lower) estimates of efficiency in other regions' metrics and is useful for comparing the energy-efficient AC models, which are likely mostly composed of VSD split ACs. Given manufacturers likely design their units specifically to perform best under the regional test procedure, obtaining more test data from multiple regions would enable more precise estimates of the performance of highly efficient ACs in each regional metric. However, our approach is suitable for initially assessing the performance of a given model or an efficiency level in a regional standard, although it is not suitable for compliance purposes.

Using model-level data on room AC efficiency in several regions, we apply the scaling relations to compare the efficiency distributions on an equal footing, including the overall distributions, specific bilateral comparisons, and global high-efficiency benchmarks. Our results suggest potential to improve AC efficiency regionally or globally. First, the most efficient room AC models sold in each region and worldwide typically are more efficient than the most efficient level recognized by regional energy S&L programs, indicating the potential for significant energy savings using commercially available technology if more stringent standards or labels were implemented. Second, AC units that currently meet the least stringent levels will save significant electricity if they attain the highest efficiencies. Even those units currently meeting the most stringent levels appear to have additional savings potentials.

The global demand for room ACs and associated energy consumption are expected to increase significantly, particularly owing to demand from emerging economies—thus, policies that promote deployment of high-efficiency ACs will become increasingly important. Easily comparable information about energy-efficient and best-available AC products available on the global market could help policymakers evaluate their AC efficiency programs and modify them to keep pace with technological improvements.

Acknowledgments

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Table 6
Interregional conversion of seasonal energy efficiency for split room ACs in Wh/Wh.

	Regional efficiency performance (X)	ISO CSPF predicted from X	% of 6248 VSD models estimated to meet the level	Regional efficiency performance (X)	ISO CSPF predicted from X	% of 6248 VSD models estimated to meet the level
	MEPS			Most stringent class		
India	3.50	3.79	99%	5.50	7.04	17%
Japan	4.50	4.68	78%	6.6	7.58	10%
China (cooling only)	5.00	6.09	39%	5.80	7.32	12%
China (heat pumps)	4.00	5.17	66%	5.00	7.59	9%
South Korea (cooling only)	3.15	3.44	100%	10.66	10.06	0.3%
EU	4.60	4.48	89%	8.50	8.82	3.5%
U.S.	4.10	4.01	97%	5.28	5.09	70%

Appendix A. Energy-efficiency standards and test parameters by region

Seasonal efficiency metrics consider the impact of variations in outdoor temperature on cooling load and energy consumption, requiring (or optionally allowing) multiple test points to compute a seasonally weighted average efficiency, and they are intended to represent how the AC would perform over a typical cooling season in a representative building type with typical operating characteristics (Econoler et al., 2011; Wu et al., 2019). The seasonal efficiency metrics used in Japan, India, and countries in Southeast Asia are equivalent to ISO 16358:2013-defined metrics.[3] Japan and India use their region-specific climatic conditions. Southeast Asian countries use the ISO reference temperature bin hours. The seasonal efficiency metrics used in China and South Korea are largely consistent with ISO 16358:2013-defined metrics, except they use their region-specific climatic conditions and different ways of calculating performance at part-load operation. The seasonal efficiency metrics, called SEERs, used in the U.S. and EU require more data points for outside temperature and part-load conditions than do those used in the ISO standard. The EU SEER also includes the impact of standby and other low-power modes. Table A1 summarizes seasonal efficiency-related standards for the select economies.

Table A1
Standards for AC energy-efficiency evaluation.

	Efficiency standards and labels	Seasonal efficiency calculation methods	Efficiency test methods	Seasonal efficiency indicators
ISO	N/A	ISO 16358-1-2013 (CSPF) ISO 16358-2-2013 (HSPF) ISO 16358-3-2013 (APF)	ISO 5151-2010	CSPF, HSPF, APF
China	GB 12021.3-2010 GB 21455-2013	GB/T 7725-2004 GB/T 17758-2010	GB/T 7725-2004 GB/T 17758-2010	SEER, HSPF, APF
EU	(EU) No 626/2011 (EU) No 206/2012	EN 14825:2016	EN 14511:2013	SEER, SCOP
India	Schedule - 19 Variable Capacity Air Conditioners	ISO 16358-1-2013	IS 1391 (Part 1 & Part 2)	SEER
Japan	Top Runner Program	JIS C 9612-2013	JIS B 8615-1:2013	CSPF, HSPF, APF
South Korea	MOTIE Notification No. 2018-99	KS C 9306:2017	KS C 9306:2017	CSPF, HSPF
U.S.	82 FR 1786 10 CFR Part 430	10 CFR part 430 Subpart B, Appendix M (refers to ANSI/AHRI Standard 210/240)	10 CFR part 430 Subpart B, Appendix M (refers to ANSI/AHRI Standard 210/240)	SEER, HSPF

CSPF (cooling seasonal performance factor); HSPF (heating seasonal performance factor); APF (annual performance factor); GB ("Guobiao" (Guóbiāo) stands for "national standard"); EN (European Standard); SCOP (seasonal coefficient of performance); IS (Indian Standards); JIS (Japanese Industrial Standards); MOTIE (Ministry of Trade, Industry, and Energy); KS (Korean Standards); FR (Federal Register); CFR (Code of Federal Regulations); ANSI (American National Standards Institute); AHRI (Air-Conditioning, Heating, and Refrigeration Institute).
Source: Authors' work based on regional documents listed in Table A1, (Asia-Pacific Economic Cooperation (APEC), 2010; Econoler et al., 2011; Xiaoli, Ning, & Zhiqiang, 2015).

The difference in seasonal efficiency metrics is primarily due to the outside temperature profiles that are used to aggregate steady-state and cyclic ratings into a seasonal efficiency value, as well as the ways of evaluating performance at part-load operation in the metric. Energy-efficiency test data for AC models in different regions can be used to estimate the performance of these models in any region- or country-specific metric if all the required test points are measured.

Table A2
Test requirements and options used for AC seasonal energy-efficiency evaluation in China, India, Japan, and South Korea.

Operating condition/type	FSD	VSD
Full capacity (35 °C)	Required	Required
Half or intermediate capacity (35 °C)[a]	Not applicable	Required
Minimum capacity (35 °C)	Not applicable	Required/optional/not considered[c]
Full capacity (29 °C)	Required/optional[b]	Optional[c]
Half or intermediate capacity (29 °C)	Not applicable	Optional[c]
Minimum capacity (29 °C)	Not applicable	Optional/not considered[c]

The ISEER calculation in India does not consider minimum capacity tests.
ISO 16358 suggests the minimum capacity test at 29 °C to be conducted first and allows the minimum capacity test at 35 °C to be measured or calculated by using default values. China (for units with CC > 7.1 kW) and South Korea standards require the minimum capacity test at 35 °C and allow the minimum capacity test at 29 °C to be calculated by using default values.
Source: (Park, Shah, Letschert, & Lamberts, 2019).

[a] The ISO 16358-1:2013, JIS C 9612-2013 (Japan), and GB/T 7725-2004 (China) standards specify cooling half-capacity at outdoor temperature t to be 50% (±5% or ±0.1 kW) of full capacity at t at full-load operating conditions. In South Korea, the KS C 9306:2017 standard is based on full- and minimum-capacity tests. The intermediate-capacity test can be done at a level between the full and minimum capacities, if the minimum capacity is <50% of the full capacity.

[b] While ISO 16358 requires full-load performance at the lower temperature to be measured, this is calculated in regional standards by using predetermined equations as below: $Capacity(29\,^\circ C) = Capacity(35\,^\circ C) \times 1.077$; $Power\ input(29\,^\circ C) = Power\ input(35\,^\circ C) \times 0.914$.

[c] Performance at the lower temperature can be calculated by using predetermined equations as below: ISO, China, India, Japan: $Capacity(29\,^\circ C) = Capacity(35\,^\circ C) \times 1.077$; $Power\ input(29\,^\circ C) = Power\ input(35\,^\circ C) \times 0.914$ South Korea: $Capacity(29\,^\circ C) = Capacity(35\,^\circ C) \times 1.077$; $Power\ input(29\,^\circ C) = Power\ input(35\,^\circ C) \times 0.864$

[3] Test procedures for ACs in these countries are based on the ISO 5151 standard. The ISO 16358:2013 standards specify the calculations for evaluating the seasonal performance factor—defined as cooling seasonal performance factor (CSPF, ISO 16358-1:2013), heating seasonal performance factor (HSPF, ISO 16358-2:2013), and annual performance factor (APF, ISO 16358-3:2013, which considers both cooling and heating efficiency for heat pumps) of equipment whose testing is covered by ISO 5151, ISO 13253, and ISO 15042.

China, India, Japan, and South Korea

Specific parameters to account for AC performance at part-load and/or lower-temperature operation in the efficiency metric vary by country. Table A2 shows requirements and options that can be used for seasonal energy-efficiency evaluation in the selected four economies.

The ISEER and Japanese CSPF calculations for VSD units require two sets of test data—measurement of performance (capacity and power input) at full- and half-capacity operation at 35 °C and another set of data points at 29 °C calculated by ISO 16358-determined equations (which are the same as the predetermined equations from JIS C 9612-2013).

The China SEER calculation for VSD units with CC ≤ 7.1 kW requires two sets of test data (performance at full- and half-capacity operation at 35 °C) and allows other test points at 29 °C to use either the Chinese standard (GB 21455-2013) determined equations or measured values. For VSD units with CC > 7.1 kW, three sets of test data (performance at full-, half-, and minimum-capacity operation at 35 °C) are required, and another set of data points at 29 °C is calculated by the Chinese standard (GB 21455-2013) determined equations or measured. Based on our communications with AC manufacturers and experts in China, all data points that can be measured or calculated are typically calculated in China.

The Korean CSPF calculation for VSD units requires three sets of test data (performance at full-, half-, and minimum-capacity operation at 35 °C), and another set of data points at 29 °C is calculated by the Korean standard (KS C 9612-2017) determined equations. Minimum capacity tests are typically conducted at the lowest capacity control settings of units that allow steady-state operation at the given test conditions.

The SEERs used in the EU and U.S. require more data points for outside temperature and part-load conditions than do those used in the Asian countries discussed above or the ISO standard (Table A3).[4]

We use country-specific outdoor temperature profiles obtained from GB 21455–2013 for China, EN 14825:2016 for the EU, Schedule 19 for India, JIS C 9612:2013 for Japan, KS C 9306:2017 for South Korea, and 10 CFR part 430 (which refers to ANSI/AHRI 210/240) for the U.S. Table A4 summarizes outdoor temperature bins used for seasonal energy-efficiency calculations in the select economies.

Degradation coefficient (CD) is a factor of efficiency loss due to the cyclic operation of an AC, which is an important parameter for on-off cycling performance evaluation. Although the value of CD is derived from experiments, we use CD = 0.25 for all regional metrics (Asia-Pacific Economic Cooperation (APEC), 2010; Econoler et al., 2011).

Table A3
Comparison of primary test conditions for VSD ACs.

ISO			U.S.			EU			
Part load (%)	Outdoor DB/WB Temp. (°C)	Indoor DB/WB Temp. (°C)	Required Test - compressor speed/cooling air volume	Outdoor DB/WB Temp. (°C) [°F]	Indoor DB/WB Temp. (°C) [°F]		Part load Ratio (%)	Outdoor DB Temp. (°C)	Indoor DB/WB Temp. (°C)
Full load	35/24	27/19	A_2 – Max/Full	35.0/23.9 [95/75]	26.7/19.4 [80/67]	A	100	35	27/19
Half load			B_2 – Max/Full	27.8/18.3 [82/65]		B	74	30	
Min load[a]			E_v – Intermediate/Intermediate	30.6/20.6 [87/69]		C	47	25	
Full load	29/19	27/19	B_1 – Min/Min	27.8/18.3 [82/65]		D	21	20	
Half load Min load[a]			F_1 – Min/Min	19.4/11.9 [67/53.5]					

DB = dry bulb, WB = wet bulb.
[a] According to ISO 16358-1:2013, minimum-load operation is defined as operation of the equipment and controls at minimum continuous capacity. 25% of minimum load is used under the Chinese standard.
Source: (Park et al., 2019).

Table A4
Summary of outdoor temperatures used in calculations of seasonal energy efficiency by region.

	China	EU	India	Japan	South Korea	U.S.
Standard	GB 21455-2013	EN 14825: 2016	Schedule 19 VSD ACs	JIS C 9612:2013	KS C 9306:2017	ANSI/AHRI 210/240-2017
Temperature range	24–38 °C	17–40 °C	24–43 °C	24–38°C[c]	24–38 °C	65–104 °F (18.3–40 °C)
Number of temperature bins	15 bins (1 °C per bin)	24 bins (1 °C per bin)	20 bins (1 °C per bin)	15 bins (1 °C per bin)	15 bins (1 °C per bin)	8 bins (5 °F per bin)
Total hours of outdoor temperature bin[a]	1136	2602[b]	1600	1569	941	Defined fraction of total temperature bin hours[c]

[a] Although JIS C 9612:2013 and KS C 9306:2017 define outdoor temperature bin hours in the range of 24–38 °C, zero hours are actually assigned to 35–38 °C in JIS C 9612:2013 and 38 °C in KS C 9306:2017.
[b] According to EN 14825:2016, an equivalent active mode hours for cooling is assumed to be 350 h, while the total hours of the outdoor temperature bin is 2602 h.
[c] Bin hours of each outdoor temperature may be calculated by multiplying the fractional bin hours by the total annual cooling hours if the fractional bin hours are applicable. ISO 16358 also provides fractional bin hours.

[4] In the EU, the four test points (A, B, C, and D) are points that manufacturers are supposed to "declare." Hence, each point does not need to be tested; the points could also be calculated based on other tested points or based on the performance of similar units.

Appendix B. Interregional conversion of seasonal efficiency performance for non-ducted split ACs

Table B1
Interregional conversion relationships of seasonal energy efficiency for split room ACs, based on the data of two FSD and four VSD models (Group A).

Y	X	$Y = d + \frac{a-d}{(1+(\frac{X}{c})^{b})}$							Alternative (linear, logarithm, or exponential)
		a	b	c	d	R^2	p-value	Std. error	
ISO CSPF	ISEER	1.847	3.269	5.473	12.156	0.999	0.002	0.134	7.726·ln(X)-5.318 (R^2 = 0.996)
	China APF	3.105	7.216	4.659	10.287	0.994	0.011	0.330	1.798·X-2.027 (R^2 = 0.970)
	Japan APF	3.348	5.036	7.349	14.855	1.000	0.001	0.087	1.735·exp. (0.220·X) (R^2 = 0.976)
	Korea CSPF	3.244	4.490	7.179	11.221	0.999	0.002	0.132	0.970·X + 0.048 (R^2 = 0.991)
	U.S. SEER	1.728	1.741	15.127	26.177	1.000	0.000	0.047	0.962·X + 0.087 (R^2 = 0.999)
	EU SEER	−0.600	1.006	521,765	617,390	1.000	0.001	0.079	1.113·X-0.639 (R^2 = 0.999)
ISEER	ISO CSPF	2.465	1.765	15,334	2,215,983	0.996	0.007	0.192	2.085·exp. (0.137·X) (R^2 = 0.996)
	China APF	2.804	4.813	5.305	9.716	0.996	0.008	0.207	1.323·X-0.883 (R^2 = 0.986)
	Japan APF	3.150	3.696	248	1,790,672	0.997	0.006	0.172	1.807·exp. (0.184·X)c (R^2 = 0.956)
	Korea CSPF	2.982	3.200	9.533	12.086	0.997	0.005	0.166	2.094·exp. (0.133·X) (R^2 = 0.992)
	U.S. SEER	2.574	1.826	11,731	2,126,699	0.998	0.005	0.159	2.108·exp. (0.132·X) (R^2 = 0.997)
	EU SEER	2.322	1.823	10,862	2,158,012	0.994	0.011	0.239	1.910·exp. (0.152·X) (R^2 = 0.995)
China APF	ISEER	−0.369	0.781	21,142,970	729,082	0.987	0.027	0.278	0.745·X + 0.723 (R^2 = 0.986)
	ISO CSPF	2.405	1.603	33,306	1,919,929	0.974	0.051	0.385	0.539·X + 1.232 (R^2 = 0.970)
	Japan APF	2.936	3.210	486	2,193,369	0.982	0.036	0.321	1.849·exp. (0.160·X) (R^2 = 0.967)
	Korea CSPF	2.215	1.455	50,896	1,076,342	0.980	0.040	0.338	0.527·X + 1.233 (R^2 = 0.976)
	U.S. SEER	2.525	1.695	21,683	1,818,168	0.975	0.049	0.377	0.519·X + 1.280 (R^2 = 0.969)
	EU SEER	2.198	1.598	29,631	1,717,656	0.973	0.053	0.391	0.600·X + 0.887 (R^2 = 0.970)
Japan APF	ISEER	−9,160,614	1.788	0.001	8.854	0.994	0.012	0.248	5.207·ln(X)-2.840 (R^2 = 0.956)
	China APF	1.763	5.614	3.953	8.002	0.987	0.027	0.370	6.061·ln(X)-3.546 (R^2 = 0.967)
	ISO CSPF	−6,822,450	0.975	2.59E-06	10.239	0.989	0.021	0.328	4.428·ln(X)-2.307 (R^2 = 0.976)
	Korea CSPF	−555,719	0.533	5.07E-09	13.961	0.990	0.019	0.315	4.399·ln(X)-2.352 (R^2 = 0.985)
	U.S. SEER	−4,881,884	0.788	1.63E-07	11.142	0.989	0.022	0.337	4.342·ln(X)-2.250 (R^2 = 0.979)
	EU SEER	−7,207,856	1.180	2.94E-05	9.904	0.992	0.017	0.290	4.923·ln(X)-3.205 (R^2 = 0.975)
Korea CSPF	ISEER	12.819	0.383	5.84E+08	23,662	0.994	0.013	0.356	7.452·ln(X)-5.456 (R^2 = 0.992)
	China APF	2.594	4.602	4.984	12.132	0.983	0.035	0.592	1.851·X-2.129 (R^2 = 0.976)
	Japan APF	2.998	2.849	616.656	1,868,831	0.996	0.008	0.281	1.740·exp. (0.224·X) (R^2 = 0.984)
	ISO CSPF	0.091	1.014	5.96E+05	707,213	0.991	0.017	0.416	1.022·X + 0.006 (R^2 = 0.991)
	U.S. SEER	0.665	1.109	6.55E+05	2,032,325	0.994	0.013	0.358	0.985·X + 0.087(R^2 = 0.993)
	EU SEER	−0.628	1.002	5.64E+05	653,666	0.989	0.022	0.465	1.136·X-0.640(R^2 = 0.989)
U.S. SEER	ISEER	1.161	2.835	5.419	13.094	0.999	0.003	0.168	7.562·ln(X)-5.620(R^2 = 0.997)
	China APF	3.063	7.031	4.635	10.600	0.992	0.016	0.408	1.868·X-2.192(R^2 = 0.969)
	Japan APF	3.309	4.721	7.489	15.957	0.999	0.001	0.115	1.723·exp. (0.226·X)(R^2 = 0.979)
	Korea CSPF	3.111	4.061	7.223	11.868	0.999	0.001	0.118	1.009·X-0.046(R^2 = 0.993)
	ISO CSPF	−0.752	0.903	972,471	350,955	1.000	<0.001	0.066	1.039·X-0.088(R^2 = 1.000)
	EU SEER	−1.557	0.895	844,487	317,559	0.973	0.053	0.391	1.155·X-0.750(R^2 = 0.999)
EU SEER	ISEER	2.387	3.469	5.424	11.236	0.999	0.003	0.140	6.536·ln(X)-4.201(R^2 = 0.995)
	China APF	3.369	7.296	4.650	9.797	0.996	0.008	0.246	1.616·X-1.247(R^2 = 0.970)
	Japan APF	3.590	5.103	7.293	13.728	1.000	<0.001	0.078	1.971·exp. (0.198·X)(R^2 = 0.975)
	Korea CSPF	3.545	4.746	7.110	10.480	0.998	0.003	0.161	0.871·X + 0.625(R^2 = 0.989)
	U.S. SEER	2.402	2.000	11.944	19.171	0.999	0.002	0.110	0.865·X + 0.656(R^2 = 0.999)
	ISO CSPF	1.329	1.348	25.506	38.589	1.000	<0.001	0.069	0.899·X + 0.576(R^2 = 1.000)

Table B2
Interregional conversion relationships (linear, Y = aX+b) of seasonal energy efficiency for VSD (inverter-driven) split room ACs, based on the data of 28 VSD models (Groups A and B).

		X					
		ISEER	China APF	Japan APF	Korea CSPF	U.S. SEER	EU SEER
Y (predicted)	ISEER	–	1.220·X-0.320 (R^2=0.977)	0.997·X-0.161 (R^2=0.935)	0.594·X+1.621 (R^2=0.922)	0.759·X-0.356 (R^2=0.775)	0.740·X-0.673 (R^2=0.474)
	China APF	0.801·X+0.348 (R^2=0.977)	–	0.811·X+0.160 (R^2=0.943)	0.481·X+1.619 (R^2=0.921)	0.602·X+0.100 (R^2=0.742)	0.541·X+0.169 (R^2=0.386)
	Japan APF	0.938·X+0.453 (R^2=0.935)	1.162·X+0.082 (R^2=0.943)	–	0.584·X+1.843 (R^2=0.947)	0.684·X+0.299 (R^2=0.668)	0.566·X+0.710 (R^2=0.295)
	Korea CSPF	1.552·X-2.1385 (R^2=0.922)	1.915·X-2.719 (R^2=0.921)	1.623·X-2.737 (R^2=0.947)	–	1.132·X-2.393 (R^2=0.550)	0.895·X-1.420 (R^2=0.265)
	U.S. SEER	1.020·X+1.799 (R^2=0.775)	1.232·X+1.521 (R^2=0.742)	0.977·X+1.824 (R^2=0.668)	0.582·X+3.569 (R^2=0.658)	–	0.924·X-0.069 (R^2=0.550)
	EU SEER	0.640·X+4.100 (R^2=0.474)	0.713·X+4.163 (R^2=0.386)	0.521·X+4.543 (R^2=0.295)	0.296·X+5.541 (R^2=0.265)	0.596·X+3.175 (R^2=0.550)	–

Gray cells represent regression relationships with high R-squared values.

Table B3
Interregional conversion relationships (logarithmic, Y = a·ln(X) + b) of seasonal energy efficiency for VSD (inverter-driven) split room ACs.

		X					
		ISEER	China APF	Japan APF	Korea CSPF	U.S. SEER	EU SEER
Y (predicted)	ISEER	–	5.418·ln(X)-2.846 (R^2=0.939)	5.272·ln(X)-3.533 (R^2=0.904)	3.569·ln(X)-0.985 (R^2=0.888)	5.135·ln(X)-4.954 (R^2=0.705)	4.724·ln(X)-4.647 (R^2=0.398)
	China APF	4.245·ln(X)-2.348 (R^2=0.969)	–	4.323·ln(X)-2.636 (R^2=0.926)	2.925·ln(X)-0.545 (R^2=0.908)	4.069·ln(X)-3.541 (R^2=0.675)	3.399·ln(X)-2.632 (R^2=0.314)
	Japan APF	4.976·ln(X)-2.710 (R^2=0.929)	5.211·ln(X)-2.392 (R^2=0.924)	–	3.567·ln(X)-0.807 (R^2=0.942)	4.595·ln(X)-3.786 (R^2=0.600)	3.484·ln(X)-2.075 (R^2=0.230)
	Korea CSPF	8.100·ln(X)-7.172 (R^2=0.886)	8.454·ln(X)-6.616 (R^2=0.875)	8.537·ln(X)-8.161 (R^2=0.907)	–	7.525·ln(X)-9.008 (R^2=0.579)	5.424·ln(X)-5.667 (R^2=0.201)
	U.S. SEER	5.303·ln(X) -1.478 (R^2=0.739)	5.384·ln(X)-0.911 (R^2=0.690)	5.057·ln(X)-1.317 (R^2=0.619)	3.382·ln(X) +1.191 (R^2=0.593)	–	6.113·ln(X)-5.441 (R^2=0.496)
	EU SEER	3.367·ln(X) +1.986 (R^2=0.462)	3.088·ln(X) +2.793 (R^2=0.352)	2.650·ln(X) +2.941 (R^2=0.264)	1.618·ln(X) +4.492 (R^2=0.211)	4.190·ln(X)-0.729 (R^2=0.543)	–

Gray cells represent regression relationships with high R-squared values.

Table B4

Interregional conversion relationships (exponential, Y = a·exp.(b·X)) of seasonal energy efficiency for VSD (inverter-driven) split room ACs.

		X					
		ISEER	China APF	Japan APF	Korea CSPF	U.S. SEER	EU SEER
Y (predicted)	ISEER	–	1.789·exp (0.228·X) (R^2=0.969)	1.842·exp (0.187·X) (R^2=0.929)	2.594·exp (0.109·X) (R^2=0.886)	1.808·exp (0.139·X) (R^2=0.739)	1.688·exp (0.137·X) (R^2=0.462)
	China APF	1.778·exp (0.173·X) (R^2=0.939)	–	1.694·exp (0.177·X) (R^2=0.924)	2.349·exp (0.103·X) (R^2=0.875)	1.708·exp (0.128·X) (R^2=0.690)	1.746·exp (0.114·X) (R^2=0.352)
	Japan APF	2.120·exp (0.172·X) (R^2=0.904)	1.968·exp (0.214·X) (R^2=0.926)	–	2.741·exp (0.106·X) (R^2=0.907)	2.096·exp (0.122·X) (R^2=0.619)	2.285·exp (0.100·X) (R^2=0.264)
	Korea CSPF	1.518·exp (0.249·X) (R^2=0.888)	1.363·exp (0.311·X) (R^2=0.908)	1.352·exp (0.264·X) (R^2=0.942)	–	1.513·exp (0.175·X) (R^2=0.593)	1.868·exp (0.130·X) (R^2=0.211)
	U.S. SEER	3.393·exp (0.137·X) (R^2=0.705)	3.270·exp (0.166·X) (R^2=0.675)	3.418·exp (0.131·X) (R^2=0.600)	4.334·exp (0.077·X) (R^2=0.579)	–	2.548·exp (0.129·X) (R^2=0.543)
	EU SEER	4.736·exp (0.084·X) (R^2=0.398)	4.803·exp (0.092·X) (R^2=0.314)	5.079·exp (0.066·X) (R^2=0.230)	5.780·exp (0.037·X) (R^2=0.201)	4.119·exp (0.081·X) (R^2=0.496)	–

Gray cells represent regression relationships with high R-squared values.

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