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Assessment of commercially available energy-efficient room air conditioners including models with low global warming potential (GWP) refrigerants

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ABSTRACT

Improving the energy efficiency of room air conditioners (RACs)[1] will be a critical step toward reducing the energy, peak load, and total lifecycle emissions impacts of RACs while transitioning to low global-warming-potential (GWP)[2] refrigerants under the 2016 Kigali Amendment to the Montreal Protocol. Previous research quantified the energy and climate benefits of leapfrogging to high efficiency in tandem with the transition to low-GWP refrigerants for RACs (Shah et al., 2015) and identified opportunities for initial action to coordinate energy efficiency with refrigerant transition, focusing initially on economies constituting about 65% of the global RAC market (Shah et al., 2017). Previous research by Oak Ridge National Laboratory (ORNL) determined that flammable HC-290 (R-290) and HFC-32 (R-32) are inherently more energy efficient than non-flammable HFC-410A (R-410A).

This report describes further research performed to identify the best-performing (i.e., most efficient and low-GWP-refrigerant using) RACs on the market to maximize the lifecycle energy, cost, direct and indirect emissions savings discussed in previous work. By defining and describing current best available technology (BAT), this report can help support market-transformation programs for high-efficiency and low-GWP equipment such as minimum energy performance standards (MEPS), labeling, procurement, performance assurance requirements for imports, and incentive programs. Furthermore, the new strategy of bulk government procurement is proving that high efficiency can be achieved at affordable cost by capturing economies of scale in production, sales, distribution, and installation (Abhyankar et al., 2017; Mathur et al., 2017).

The report focuses more on RACs that maximize efficiency as long as the GWP of refrigerant is marginally lower than the baseline, for the following reasons:

- Energy related indirect emissions typically dominate carbon footprint over the lifecycle of the RACs jurisdictions where the carbon intensity is high from fossil fuel and biomass electricity generation but are insignificant in jurisdictions where the carbon intensity is low from nuclear, wind, solar, and geothermal electricity generation. (Goetzler et al., 2016).
- With the adoption of the Kigali Amendment there is a global agreement to phasedown high GWP HFCs, with two associated decisions addressing energy efficiency (XXVIII 2 and 3)
- The technology used in the highest efficiency RACs with high GWP non-flammable refrigerants is similar to technology used in RACs with flammable low-GWP refrigerants.

We studied RACs available in six economies—China, Europe, India, Japan, South Korea, and the United States—that together account for about 70% of global RAC demand, as well as other emerging economies. The following are our key findings:

[1] This study focuses on ductless split ACs, because the global RAC market is dominated by this type of unit, known in the United States as mini-splits.
[2] We use the term “low-GWP” to mean “lower than the baseline refrigerant being replaced.”

- Fixed-speed RACs using high-GWP and ozone-depleting R-22 refrigerant still dominate the market in many emerging economies. Because of the prevalence of fixed-speed RACs using R-22 in many markets among the Article 5 (A5) Parties, there is significant opportunity to improve RAC efficiency and transition to low-GWP refrigerants using commercially available technology and to design market-transformation programs for high-efficiency, low-GWP equipment, including standards, labeling, procurement, performance assurance requirements for imports, and incentive programs.
- Highly efficient RACs using low-GWP refrigerants, e.g., R-32 and R-290 are commercially available today at prices comparable to similar RACs using high-GWP HCFC-22 (R-22) or R-410A. R-290 RACs are manufactured only in China and India and have only penetrated the Indian market, but 30 million R-32 ACs have been sold in ~50 countries with manufacturing in China, European Union, India, Indonesia, Japan, South Korea, Philippines, and United States.[3]
- High efficiency is typically a feature of high-end products selling at substantially higher prices than less efficient low-end products. However, highly efficient, cost-competitive (less than 1,000 or 1,500 U.S. dollars in retail price, depending on size) RACs are increasingly available in some markets.[4]
- Where R-22 is phased out, high GWP R-410A still dominates RAC sales in most non-A5 Parties except Japan, where R-32 RACs are 100% of sales.
- In all of the economies studied except Japan and India, only a few models are both energy efficient ***and*** use low-GWP refrigerants.
- RACs are available in most regions and worldwide that surpass the highest efficiency levels recognized by labeling programs, suggesting considerable opportunity to strengthen this and related market transformation programs.

[3] Updated September 2017 by Stephen O. Anderson from information provided by Daikin.

[4] In China, the price of 1-ton variable-speed ACs is estimated to be about USD 640 on average, ranging from about USD 300 to USD 1950, while that of 1-ton fixed-speed ACs is about USD 360 on average, ranging from USD 250 to USD 600.

ACRONYMS

A5	Article 5
AC	air conditioner
AHRI	Air-conditioning, Heating, and Refrigeration Institute
APF	annual performance factor
ASEAN	Association of Southeast Asian Nations
BAT	best available technology
BEE	Bureau of Energy Efficiency
Btu/h	British thermal units per hour
CC	cooling capacity
CEE	Consortium for Energy Efficiency
CFC	chlorofluorocarbons
CNIS	China National Institute of Standardization
CO_2	carbon dioxide
COP	coefficient of performance
CSPF	cooling seasonal performance factor
ECCJ	Energy Conservation Center Japan
EER	energy-efficiency ratio
EER_{IDN}	Indonesian EER
EU	European Union
EU SEER	European Union seasonal energy-efficiency ratio
GHG	greenhouse gas
GWP	global warming potential
h	hour
HC	hydrocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
HSPF	heating seasonal performance factor
IDEA	International Database of Efficient Appliances
IDU	indoor unit
IGSD	Institute for Governance and Sustainable Development
ISEER	India seasonal energy-efficiency ratio
ISO	International Organization for Standardization
JARN	Japan Air Conditioning, Heating and Refrigeration News
KEA	Korea Energy Agency
kW	kilowatt
LBNL	Lawrence Berkeley National Laboratory
MEMR	Ministry of Energy and Mineral Resources of the Republic of Indonesia

MEPS	minimum efficiency performance standards
mm	millimeters
NH_3	ammonia
ODU	outdoor unit
OEM	original equipment manufacturer
RAC	room air conditioner
RT	refrigeration ton
S&L	standards and labeling
SCOP	seasonal coefficient of performance
SEER	seasonal energy-efficiency ratio
SHINE	Standards Harmonization Initiative for Energy Efficiency
USD	U.S. dollar(s)
US DOE	U.S. Department of Energy
US SEER	United States seasonal energy-efficiency ratio
VRF	variable refrigerant flow

Executive Summary

Background and motivation

Driven by increasing incomes, electrification, urbanization, as well as a warming world, demand for room air conditioners (RACs) in emerging economies, particularly those with hot climates, is expected to greatly increase energy consumption. In the absence of implementation action under the Kigali Amendment to the Montreal Protocol, this increased demand would also greatly increase the use of high-GWP hydrofluorocarbon (HFC) refrigerants (Zaelke et al., 2017; Velders et al., 2009); in 2050, prior to the Kigali Amendment, Article 5 (A5) Parties[5] were expected to account for more than 80% of global HFC use (Seidel et al., 2016). Improving the energy efficiency of RACs[6] while transitioning to low GWP[7] refrigerants will be a critical step toward reducing the energy, peak load, and emissions impacts of ACs while keeping costs low. Previous research quantified the energy and climate benefits of leapfrogging to high efficiency in tandem with the transition to low-GWP refrigerants for RACs (Shah et al., 2015) and identified opportunities for initial action to coordinate energy efficiency with refrigerant transition in economies constituting about 65% of the global RAC market (Shah et al., 2017).

This report describes further research performed to identify the best-performing (i.e., most efficient and low-GWP-refrigerant using) RACs on the market at the time of this study, to support an understanding of the best available technology (BAT). Understanding BAT can help support market-transformation programs for high-efficiency and low-GWP equipment such as minimum energy performance standards (MEPS), labeling, procurement, performance assurance requirements for imports, and incentive programs by providing evidence to policymakers on:

- Technical potential for efficiency improvement
- Cost of efficient technology
- Technology drivers and key components for manufacturing efficient equipment
- Input into further research, e.g., testing, design, etc.
- Global dynamics regarding leading manufacturers

[5] In 2016, the Parties to the Montreal Protocol adopted the Kigali Amendment to the Montreal Protocol to agree on a global schedule for phasing down HFC refrigerants. The schedule consists of three groups of Parties, each with a target phasedown date. Many of the A5 Parties, including China, Brazil, and all of Africa, will freeze the use of HFCs by 2024. Collectively this group is known as "Group 1" of the A5 Parties. A small group of A5 Parties with the world's hottest climates—such as Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates—have the most lenient schedule and will freeze HFC use by 2028. Collectively this group is known as "Group 2" of the A5 Parties See http://ozone.unep.org/en/article-5-parties-status for the list of the Parties included as A5 Parties.

[6] This study focuses on ductless split ACs, because the global RAC market is dominated by this type of unit, often referred to as mini-splits.

[7] We use the term "low-GWP" to mean "lower than the baseline refrigerant being replaced."

Scope and methods

This report focuses more on RACs that maximize efficiency as long as the GWP of refrigerant is marginally lower than the baseline, for the following reasons:

- Energy related indirect emissions are typically the dominant type of emissions over the lifecycle of the RACs (Goetzler et al., 2016).
- With the adoption of the Kigali Amendment there is a global agreement to phasedown high GWP HFCs, with two associated decisions addressing energy efficiency (XXVIII 2 and 3)
- The technology used in the highest efficiency RACs with high GWP refrigerants is likely similar to equivalent technology used in RACs with low-GWP refrigerants with some modifications for refrigerant.

To identify energy-efficient RACs with conventional (e.g., HCFC-22 and HFC-410A, hereafter referred to as R-22 and R-410A) and low-GWP (e.g., HFC-32, HC-290, hereafter referred to as R-32 and R-290) refrigerants, we studied RACs available in six economies—China, Europe, India, Japan, South Korea, and the United States—that together account for about 70% of global RAC demand, as well as other emerging economies (JRAIA, 2017). We collected data, from March 2016 to July 2017, depending on economy, from a) coordination with the Lawrence Berkeley National Laboratory (LBNL) International Database of Efficient Appliances (IDEA) initiative, b) country-specific databases such as those of the Energy Conservation Center Japan (ECCJ) and the Korea Energy Agency (KEA), c) websites such as Topten China and Topten EU (which provide information on the most efficient appliances and equipment, including RACs), d) web searches and manufacturer catalogs; and e) interviews with industry experts. The LBNL IDEA data used in this study were collected for RACs from retail sites in China, India, Indonesia, and the United States. The IDEA software combined the information from these sites and cross-referenced the resulting models against certification data from the national appliance standards and labeling programs to validate the information collected from retail sites and ensure the models listed are available on the market at the time of this study.

This report does the following:

1. Provides a brief overview of RAC energy-efficiency and refrigerant trends.
2. Categorizes RAC products according to key characteristics, e.g., type (cooling-only or reversible), compressor technology (fixed or variable speed), and cooling capacity.[8]
3. Analyzes the RAC efficiency distribution and leading manufacturers in each market based on the most recent available data.

[8] Other features e.g. standby power, air filtration etc. may impact energy use but are not separately considered here since: a) these are not uniformly reported either online or in product databases, b) these are not covered under the standard test procedures and c) these may tend to be associated more with higher end products.

4. Reviews the data collected from the economies to select highest-efficiency RAC products in each category along with refrigerant and price information that we collected.
5. Discusses the implications of our findings and possible future research.

Key findings

The following are our key findings:

- Fixed-speed RACs using high-GWP and ozone-depleting R-22 refrigerant still dominate the market in many emerging economies. Because of the prevalence of fixed-speed RACs using R-22 in many markets among the A5 Parties, there is significant opportunity to improve RAC efficiency and transition to low-GWP refrigerants using commercially available technology and to design market-transformation programs for high-efficiency, low-GWP equipment, including standards, labeling, procurement, performance assurance requirements for imports, and incentive programs.
- BAT products, i.e., highly efficient RACs using low-GWP refrigerants (R-32 and R-290) are commercially available today at prices comparable to similar RACs using high-GWP R-22 or R-410A.
- Where R-22 is being phased out, high-GWP R-410A still dominates RAC sales in most mature markets except Japan, where R-32 dominates. From 2012, manufacturers in Japan, anticipating a transition to lower-GWP refrigerants, began a second transition from R-410A to R-32. In India, Godrej is making the transition directly from R-22 to R-290, while Daikin India introduced R-32 RACs in new production.
- In all of the economies studied except Japan, currently only a few models are energy efficient *<u>and</u>* use low-GWP refrigerants.[9]
- RAC manufacturers in China have developed R-290 products although the Chinese market also has highly-efficient R-32 RAC models.[10]
- Variable-speed or inverter products that already dominate mature RAC markets such as Europe, Japan, and South Korea are currently driving high efficiency in RACs.
- RACs are available in most regions and worldwide that surpass the highest efficiency levels recognized by labeling programs (Figure ES-1).
- While highly efficient, cost-competitive (less than 1,000 or 1,500 U.S. dollars in retail price, depending on size) RACs are available (Figure ES-2), high efficiency is typically bundled as a feature of high-end products.

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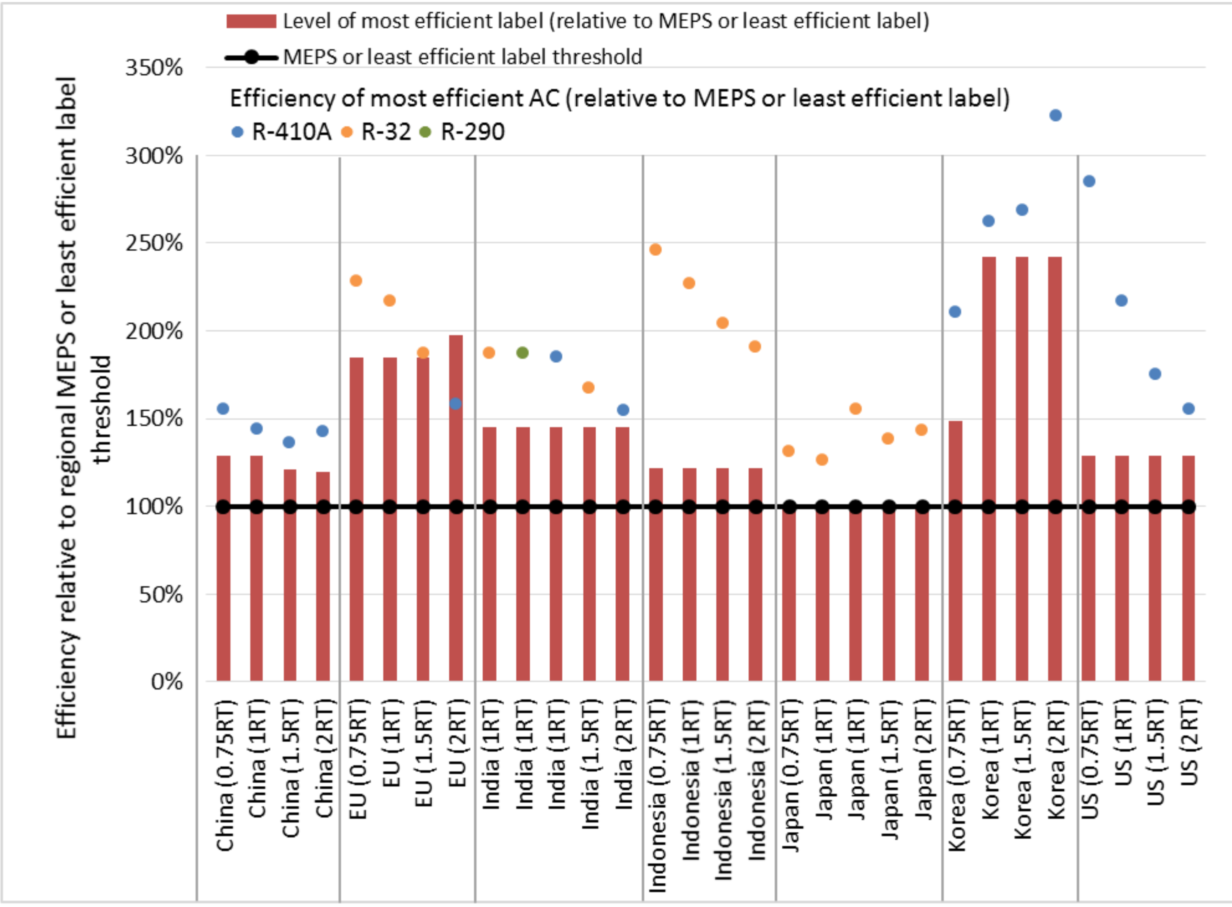
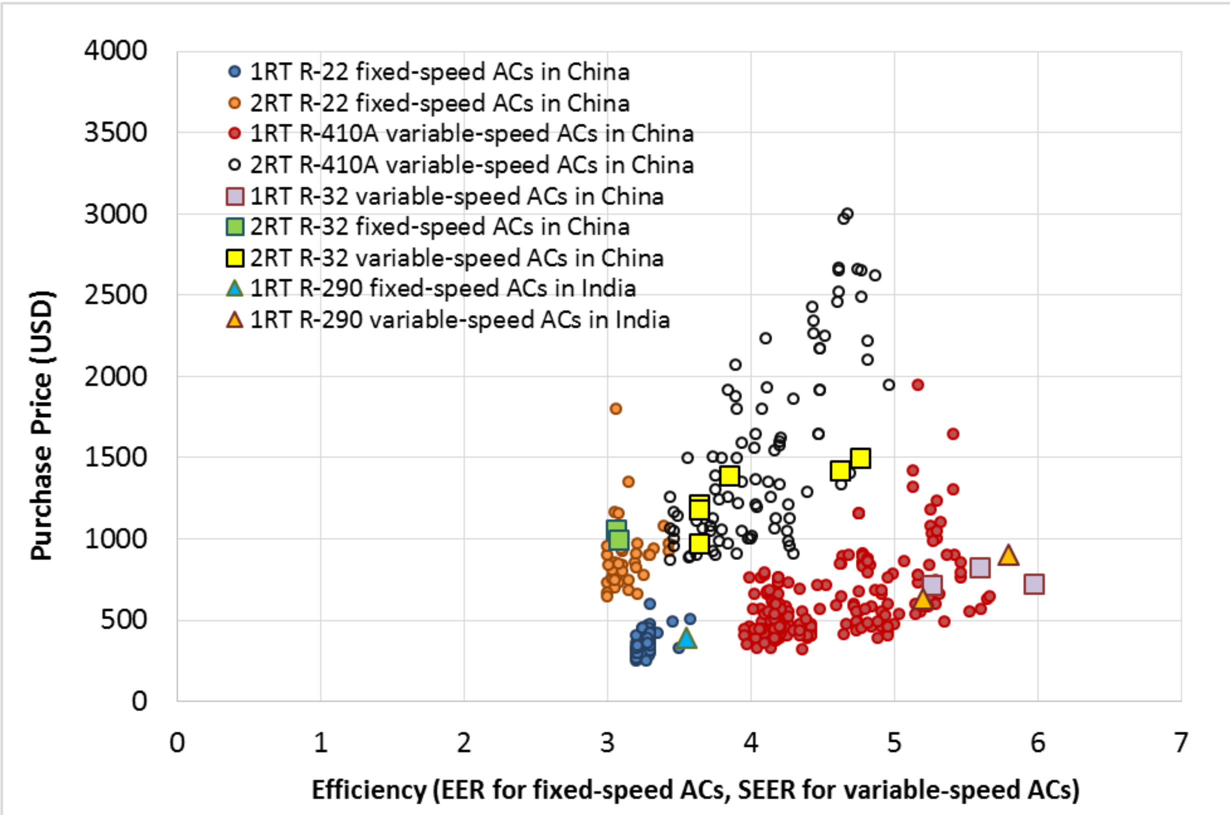
[9]Note: Low-GWP refrigerants e.g. R-32 and R-290 tend to be more efficient than the baseline units, so there is no inherent barrier to high efficiency in ACs with low-GWP refrigerants.
[10] In China, no sales of R-290 RACs were reported until July 2017 according to interviews with manufacturers and JARN (2015), except for installations for demonstration purpose. In 2017, 100,000 units of R-290 ACs are likely to be delivered from China to other markets, e.g., the Middle East and Vietnam (McLaughlin, 2017)



See Table B1 in Appendix B for information on AC models analyzed.

Figure ES-1. Efficiency of most-efficient models relative to MEPS or least-efficient labels



Number of models: 74 (1-RT R-22 fixed-speed in China), 40 (2-RT R-22 fixed-speed in China), 208 (1-RT R-410A variable-speed in China), 92 (2-RT R-410A variable-speed in China), 3 (1-RT R-32 variable-speed in China), 2 (2-RT R-32 fixed-speed in China), 6 (2-RT R-32 variable-speed in China), 1 (1-RT R-290 fixed-speed in India), 2 (1-RT R-290 variable-speed in India)
In China, the price of 1-ton variable-speed ACs is estimated to be about USD 640 on average, ranging from about USD 300 to USD 1950, while that of 1-ton fixed-speed ACs is about USD 360 on average, ranging from USD 250 to USD 600.
Source: LBNL IDEA and web searches

Figure ES-2. Price vs. efficiency of 1-RT and 2-RT RACs

Further work

The highest-efficiency, low-GWP-refrigerant using, RAC models need to be further analyzed to estimate the technical potential for efficiency improvement, cost reduction, and deployment of low-GWP refrigerants. Prices in many markets (e.g., Japan, South Korea, and India) have continued to fall over time, even with increases in efficiency (Phadke et al., 2017a; Abhyankar et al., 2017).

In light of this evidence, engineering analysis is a suitable approach to estimating an appliance's potential for reduced energy consumption and associated incremental cost of efficiency improvements. Engineering analysis is a bottom-up, static approach that has been employed in the U.S. and European Union (EU) efficiency standards rulemaking processes as well as by the Bureau of Energy Efficiency in India. When coupled with estimates for retail mark-up, this method typically provides a conservative (higher) estimate of the increase in manufacturing cost and retail price that might occur if efficiency were improved. To make the estimate even more conservative, it can be based on an estimate of the markup for baseline models, which includes typical wholesale and retail costs.[11] This approach could form the basis for conservative estimates of cost-benefit calculations related to individual consumers, manufacturers, and countries or regions to account for the additional costs, if any, compared to manufacturing conventional products.

For all refrigerants, including R-22 and R-410A[12], RAC efficiency degrades with increased ambient temperature. However, research indicates that low-GWP refrigerants could have comparable or better performance than conventional refrigerants (R-22 or R-410A) in high-ambient-temperature environments (Abdelaziz et al., 2015). Given that energy-savings potential from RACs coupled with low-GWP refrigerants could vary by regional characteristics such as local climatic conditions and projected RAC demand, there could be opportunities to achieve larger energy savings by adopting regional seasonal energy efficiency metrics in many countries, including those with hot climates.

[11] For example, Shah et al. (2016) estimated retail markups in India at ~140% on a manufacturing cost of Rs. 14500 for a baseline 1.5 ton mini-split AC.
[12] Note: R-22 is subject to phaseout under the Montreal Protocol and R-410A is now also subject to phaseout under the Kigali Amendment to the Montreal Protocol.

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1. Introduction

Driven by increasing incomes, electrification, urbanization, and a warming world, demand for air conditioners (ACs) in emerging economies with hot climates is expected to greatly increase energy consumption. In the absence of implementation action under the Kigali Amendment to the Montreal Protocol, [13] this increased demand would also greatly increase the use of hydrofluorocarbon (HFC) refrigerants, which are replacing hydrochlorofluorocarbons (HCFCs); in 2050, absent the Kigali Amendment, Article 5 (A5) Parties would have been expected to account for more than 80% of global HFC use (Seidel et al., 2016). HFCs are currently the fastest-growing greenhouse gases (GHGs), growing at the rate of 10%–15% every year. Improving the energy efficiency of room ACs (RACs)[14] while transitioning to low global warming potential (GWP)[15] refrigerants is critical to reducing the energy and emissions impacts of the growing number of RACs (Shah et el., 2017), while keeping implementation costs lower than they would be if these activities were undertaken separately. This report provides analysis and evidence to support establishment of energy-efficiency market-transformation programs such as standards, labeling, procurement, performance assurance requirements for imports, and incentive programs for RACs, which could also include a low-GWP refrigerant criterion.

Energy-efficiency policies can accelerate the adoption of cost-competitive, highly efficient appliances and equipment to save energy, lower consumer electricity costs, shave peak load, improve air quality, and reduce GHG emissions. The threshold at which products are recognized as “highly efficient” is typically informed by the technical feasibility, commercial availability, and cost-effectiveness of products that meet efficiency thresholds. Large multinational manufacturers supply a significant share of RAC markets in most regions. Therefore, an understanding of the highest-efficiency products available in several regions of the world will aid policymakers in designing effective energy-efficiency market-transformation programs.

Formulating an energy-efficiency standard or other market transformation policy that considers reduction of HFC and HCFC refrigerants requires information on the efficiency, refrigerants, and costs of commercially available RACs. Because this information is often not readily available, we address this data gap by performing an initial market assessment of energy-efficient RACs based on the most current data at the time of our research. The information we have compiled (from

[13] In 2016, the Parties to the Montreal Protocol adopted the Kigali Amendment to the Montreal Protocol to agree on a global schedule for phasing down HFC refrigerants. The schedule consists of three groups of Parties, each with a target phasedown date. Many of the A5 Parties, including China, Brazil, and all of Africa, will freeze the use of HFCs by 2024. Collectively this group is known as “Group 1” of the A5 Parties. A small group of A5 Parties with the world’s hottest climates—such as Bahrain, India, Iran, Iraq, Kuwait, Oman, Pakistan, Qatar, Saudi Arabia, and the United Arab Emirates—have the most lenient schedule and will freeze HFC use by 2028. Collectively this group is known as “Group 2” of the A5 Parties. See http://ozone.unep.org/en/article-5-parties-status for the list of the Parties included as A5 Parties.

[14] This study focuses on ductless split ACs, because the global RAC market is dominated by this type of unit, known in the United States as mini-split ACs.

[15] We use the term “low-GWP” to mean “lower than the baseline refrigerant being replaced.”

March 2016 to July 2017, depending on economy, see Table 2) gives an up-to-date understanding of the best available technology (BAT) levels of energy-efficient and low-GWP RACs in various markets. This information can then be an input for research to determine a cost-efficiency relationship for RACs and to test and model the highest-efficiency units. Such cost-efficiency relationships can inform the design of market transformation programs for high efficiency and low-GWP refrigerant using equipment such as standards, labeling, procurement, performance assurance requirements for imports, and incentive programs.

The remainder of this report is organized as follows. Section 2 gives a brief overview of RAC energy-efficiency and refrigerant trends. Section 3 describes the data sources and methodology we employ to identify energy-efficient RACs and obtain information on the price of and refrigerants used in each model. Section 4 describes energy-efficient RACs available in the economies studied. Section 5 discusses the implications of our findings and possible future research.

2. Overview of air-conditioner energy-efficiency and refrigerant trends

Although designs and configurations vary by regional market, most ACs sold today use a vapor-compression refrigeration cycle. Ductless split AC systems, on which this study focuses, are common in the residential and commercial sectors almost everywhere except in the United States, where ducted systems currently dominate but "mini-split" (ductless) systems have a gradually increasing market share (Goetzler et al., 2016). RAC cooling capacities typically range from 1.75 to 18 kW (or 0.5–5 refrigeration tons [RT][16]).

Energy efficiency and efficiency metrics

AC manufacturers continue to research and develop advanced technologies to improve performance and reduce system costs. For example, variable-speed (or inverter) products that make ACs highly efficient already dominate mature AC markets such as Australia, Europe, Japan, and South Korea. Variable-speed 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 fixed-speed compressors that cycle on and off (Shah et al., 2013).

Along with this trend, seasonal energy efficiency ratio (SEER) metrics have been designed to estimate AC performance, based on part- and full-load operations at multiple temperature conditions depending on climate. Local climatic conditions affect the amount of time an AC operates at part or full load, so climate-specific weighting is used in calculating SEER to provide a more representative measure of performance than the traditional energy-efficiency ratio (EER), typically defined as rated cooling capacity (CC) over rated power input.[17] Difference in test conditions and climate-specific weighting mean that direct conversion between regional metrics is not possible. Appendix D provides a table for approximate conversion based on linear regression of actual test data. These conversions are not sufficiently accurate to convert the performance of individual models, but may be used to compare relative regional efficiency levels and metrics.

Although fixed-speed RAC units still dominate the markets in developing countries, the market share of variable-speed RAC units is increasing.[18] For example, the market share in sales of variable-speed RACs in China, the world's largest RAC market, increased from 8% in 2007 to 65% in 2016 (Li et al., 2016; JARN, 2017b). In India, variable-speed ACs—which account for about

[16] Refrigeration tons indicate the nominal CC of the equipment where 1 ton = 12,000 Btu/h = 3.52 kW.
[17] The International Organization for Standardization (ISO) standard 5151 defines EER as the ratio of the total CC to the effective power input to the device at any given set of rating conditions, and it defines coefficient of performance (COP) as the ratio of the heating capacity to the effective power input to the device at any given set of rating conditions. We note that EER and COP have alternative definitions in certain regions.
[18] Note: Shah et al (2016) found switching from fixed speed to inverter ACs saved ~21-26% of energy at an incremental manufacturing cost of ~Rs 3600 – Rs 6300 (~US$55-96) i.e. roughly 25% incremental cost over a baseline of Rs 14,500.

10% of wall-mounted split AC products—are the fastest-growing category, achieving about a 40% growth rate in sales between 2015 and 2016 (JARN, 2017i). The market share of variable-speed RACs in Southeast Asia varies by country, from 5% to over 30%, and it is reported to be increasing every year (JARN, 2016b). Typically, sales of variable-speed ACs tend to increase when the energy savings from part-load operation due to the variable speed compressors are fully accounted for in a seasonal metric (e.g. Seasonal Energy Efficiency Ratio (SEER) or Annual Performance Factor (APF)). Hence, adopting SEER metrics will help further capture opportunities for reducing future energy consumption, particularly in countries where large seasonal variations in climate result in ACs running at part load for a larger amount of time (Shah et al., 2013).

Refrigerants

Refrigerants have changed several times, with the goal of improving safety and performance and reducing environmental impacts. First-generation refrigerants were non-fluorinated substances such as hydrocarbons (HCs), ammonia (NH_3), and carbon dioxide (CO_2). Second-generation refrigerants were chlorofluorocarbons (CFCs, e.g., R-12) and HCFCs (e.g., R-22), which are efficient, non-flammable, and non-toxic, but ozone-depleting and high GWP. Third-generation refrigerants are HFCs (e.g., R-410A and R-134a), which are non-ozone depleting but often have high GWP. Until 2012, most AC manufacturers making a transition from R-22 chose R-410A, which is now the most widely used refrigerant in high-efficiency RACs. However, from about 2012, some Japanese manufacturers began a second transition from R-410A to R-32. The Indian manufacturer Godrej leapfrogged R-410A and is making the transition directly from R-22 to R-290. These transitions represent the trend toward fourth-generation refrigerants, which include low-GWP HFCs (e.g., R-32), hydrofluoroolefins (HFOs) or HFO blends (e.g., R-452B, R-1234yf), and natural refrigerants such as HCs (e.g., R-290) (Goetzler et al., 2016). Although current technologies, including high-GWP refrigerants, can provide high-efficiency performance, the ongoing transition to low-GWP refrigerants poses challenges for manufacturers developing and deploying new products. Table 1 shows time frames and examples for each generation of refrigerants.

Table 1. Refrigerant transitions over time

Refrigerant Category	Time Frame	Example Refrigerants
1st Generation ("Toxic and Flammable")	1830–1930	HCs (butane, propane, naphtha, gasoline), NH_3, carbon disulfide, carbon dioxide, carbon tetrachloride, dichlorethylene, ethane, ethylamine, ethyl bromide, methyl bromide, methyl formate, methylene chloride, methylamine, methyl chloride, trichloroethylene, and trimethylamine (Andersen et al., 2013)
2nd Generation ("Safe and Durable") but Ozone-Depleting	1931–1990	CFCs, HCFCs (e.g., R-12, R-22)
3rd Generation ("Ozone-safe")	1990–2010	HFCs (e.g., R-410A, R-134a)[19]
4th Generation ("Ozone-safe and Lower GWP")	2010–now	Low-GWP HFCs and blends (e.g., R-32 and R-452B), low-GWP HFOs (e.g., R-1234yf), and HCs (e.g., R-290), and others
5th Generation ("Super-efficient and Sustainable" Low-GWP)	2017–future	

We added the 5th generation to the 1st to 4th generations based on Calm (2008) and Goetzler et al. (2016). Andersen et al. (2013) distinguish two periods in the 1st generation: first toxic and flammable refrigerants used in industrial facilities or to produce manufactured ice used in both commercial and residential applications and later toxic and flammable refrigerants used in appliances in commercial and residential applications.

[19] HFC 123 is low ODP, low GWP and energy efficient.

3. Data

To identify energy-efficient, affordable RACs with both conventional (e.g., R-410A) and low-GWP (e.g., R-32, R-290) refrigerants, this report explores RAC products available primarily in six economies—China, Europe, India, Japan, South Korea, and the United States—that account for about 70% of global RAC demand, plus other developing economies in Southeast Asia (JRAIA, 2017). The data were collected from a) coordination with the Lawrence Berkeley National Laboratory (LBNL) International Database of Efficient Appliances (IDEA) initiative; b) country-specific databases such as those of the Energy Conservation Center Japan (ECCJ) and the Korea Energy Agency (KEA); c) websites such as Topten China and Topten EU, which provide information on the best-performing appliances and equipment, including RACs; d) web searches and manufacturer catalogs; and e) interviews with industry experts. The LBNL IDEA data used in this study were collected for ACs from retail sites in China, India, Indonesia, and the United States (from March 2016 to July 2017, depending on economy, see Table 2). The LBNL IDEA software combined the information from these sites and cross-referenced the resulting models against certification data from the national appliance standards and labeling (S&L) programs. The subsections below describe each data source and methodology used in our analysis.

China

We obtained a data set of about 2,000 models from the IDEA, which automatically collects information at regular intervals from an array of online retailers and manufacturer websites across different markets and appliance categories (see Gerke et al., 2017 for more details about the database). The IDEA AC data used in this study were collected in 2016 from retail sites in China. The IDEA software combined the information from these sites and cross-referenced the resulting models against the certification data from the China National Institute of Standardization (CNIS) appliance S&L program to ensure that only models available on the market are listed.[20] From the data, we identified 578 variable-speed AC models for which we have sufficient information to evaluate efficiency and retail price.

We additionally reviewed the models listed by Topten (approximately 50 energy-efficient models), which provides information on the most efficient appliances and equipment, including RACs, in that country and China's Energy Efficiency "Top Runner" Program[21] (45 models), which is designed to distinguish super-efficient models, listed in March 2016. This report shows the efficiency distribution of the 578 models identified from the IDEA as well as the highest-efficiency models selected from all available sources (see Section 4.1).

- LBNL IDEA

[20] Not all models registered to the government database may be searchable online.
[21] In December 2014, China announced plans to implement a voluntary Energy Efficiency Top Runner Program to help distinguish super-efficient models, with possible future subsidies for super-efficient products. Qualifying products that are recognized as Energy Efficiency Top Runners based on their score ranking will receive an "Energy Efficiency Top Runner" designation on the China Energy Label (Shah et al., 2017).

- Products listed in the CNIS database
- Topten China
- Energy Efficiency "Leader" ("Top Runner") China

Europe

We obtained a data set of 96 energy-efficient models listed in November 2016 on the Topten EU website, which provides information on the most efficient appliances and equipment, including RACs, in the European Union (EU) countries. We collected information on price and additional high-efficiency models through web searches. This report shows the efficiency distribution of the 96 models and selected highest-efficiency models (see Section 4.2).

- Topten EU
- Web searches

India

We obtained a data set of 785 models from the IDEA, including 472 fixed-speed models, 16 variable-speed models, and 297 unspecified models, based on the AC data collected in 2016 from retail sites in India. The IDEA software combined the information from these sites and cross-referenced the resulting models against the data associated with the Indian Bureau of Energy Efficiency (BEE) appliance Star Rating program. From the data, we identified 11 variable-speed AC models for which information is sufficient to evaluate efficiency. We also obtained a data set of 123 highest-efficiency AC models listed in February 2017 on a website (Bijli Bachao) that is an Indian equivalent of Topten, of which 73 are fixed speed and 50 are variable speed. Four of the 11 variable-speed models selected from the IDEA were included in Bijli Bachao's top 10 most-efficient ACs list. Based on these two data sets and recent reports, we finally selected 57 energy-efficient AC models in India. This report shows the efficiency distribution of the 57 energy-efficient models and selected highest-efficiency models (see Section 4.3).

- Bijli Bachao website
- Bureau of Energy Efficiency, Government of India
- LBNL IDEA

Japan

We obtained a data set of about 2,900 models (all reversible-type products, which have both cooling and heating functions, i.e., heat pumps, registered from October 2006 to September 2016) from the ECCJ database. Products registered from 2014 to 2016 account for 54% of the database. We collected price information through web searches. This report shows the efficiency distribution of 2,922 models and selected highest-efficiency models (see Section 4.4).

- Energy Conservation Center Japan database
- Price information (last access on March 2017)

South Korea

We obtained two data sets totaling approximately 2,000 models available in South Korea from the KEA database. These products were registered to the database between January 2013 and November 2016. We collected price information through web searches. This report shows the efficiency distribution of 1,309 cooling-only and 638 reversible models as well as selected highest-efficiency models (see Section 4.5).

- Korea Energy Agency database
- Price information (last access on March 2017)

United States

Although split ACs in the United States are primarily ducted systems, this report uses efficiency data for ductless split (mini-split) ACs. We obtained a data set of 836 mini-splits from the IDEA. The IDEA data used in this study were collected in 2017 from U.S. retail sites. The IDEA software combined the information from these sites and cross-referenced the resulting models against data from the U.S. Department of Energy (US DOE) Compliance Certification Database. We also reviewed data of mini-splits registered to the databases of the Consortium for Energy Efficiency (CEE) Directory of Efficient Equipment (supported by the Air-Conditioning, Heating and Refrigeration Institute [AHRI]) and the ENERGY STAR Most Efficient program. This report shows the efficiency distribution of 836 models and selected highest-efficiency models (see Section 4.6).

- LBNL IDEA
- U.S. Department of Energy's Compliance Certification Database
- CEE-AHRI Directory of Efficient Equipment database
- ENERGY STAR Most Efficient program

Other countries

We provide RAC market information for Indonesia and the Philippines, where affordable but relatively less-efficient RACs are still dominant. We obtained a data set of 335 RACs from the IDEA. The IDEA data used in this study were collected in 2017 from retail sites in Indonesia. The IDEA software combined the information from these sites and cross-referenced the resulting models against data from Indonesia's Ministry of Energy and Mineral Resources (MEMR) database. We also obtained a data set of RACs from the Philippine Department of Energy database. We discuss recent market trends in developing countries based on information from commercially available sources such as *Japan Air Conditioning, Heating and Refrigeration News* (JARN).

Table 2 summarizes the region-specific data collected for this analysis.

Table 2. Summary of primary data sources

Region	Sources	AC Models Analyzed
China	▪ LBNL IDEA (updated 07/2016) ▪ CNIS database ▪ Topten China (updated 03/2016) ▪ Top Runner China (listed 03/2016)	▪ 578 variable-speed AC models (all reversible type) from LBNL IDEA ▪ Highest-efficiency models selected from all available sources
EU	▪ Topten EU (updated 11/2016)	▪ 96 highest-efficiency single split AC models (all reversible type)
India	▪ LBNL IDEA (updated 09/2016) ▪ BEE database ▪ Bijli Bachao (updated 02/2017)	▪ 57 highest-efficiency variable-speed AC models (all cooling-only type) selected from the two sources
Japan	▪ ECCJ database (registered 10/2006–09/2016)	▪ 2,922 split AC models (all reversible type)
South Korea	▪ KEA database (registered 01/2013–11/2016)	▪ 1,309 cooling-only AC models ▪ 638 reversible-type AC models (heat pumps)
United States	▪ LBNL IDEA (updated 07/2017) ▪ US DOE Compliance Certification Database ▪ CEE-AHRI Directory of Efficient Equipment ▪ ENERGY STAR Most Efficient 2017	▪ 836 mini-split models from LBNL IDEA ▪ Highest-efficiency models selected from all available sources
Indonesia	▪ LBNL IDEA (updated 02/2017) ▪ MEMR database	▪ 335 AC models from LBNL IDEA
Philippines	▪ Government database	▪ 697 split AC models from the government database

Price information for ACs in the European Union (EU), Japan, and South Korea was collected through web searches between November 2016 and March 2017.

4. Review of energy-efficient air conditioners by region

This section reviews RAC performance data by region and product category, and it identifies RAC models for further analysis. We begin by categorizing RAC products based on key characteristics, i.e., type (cooling-only/reversible, fixed-speed/variable-speed) and size by CC. We select energy-efficient products in each product category for the eight economies studied. We then review the selected products by refrigerant and price data. Energy-efficiency S&L requirements for RACs in the EU, India, and the United States do not differ by CC—that is, S&L requirements do not decrease as CC increases. However, China, Japan, South Korea, and some other Asian countries set different S&L requirements by CC, because the energy efficiency of AC compressors (e.g., rotary compressors) tends to decrease as the size (CC) increases. Major AC manufacturers typically optimize compressor efficiency by taking advantage of the fact that variable-speed compressors can operate at a wide range of frequencies. Table 3 shows the product categories by CC considered in this study and S&L programs of China, Japan, and South Korea.

Table 3. Product categories by CC considered in this study and S&L programs of China, Japan, and South Korea

<table>
<tr><td></td><td colspan="10">CC (values in kW unless otherwise specified)</td></tr>
<tr><td>This study</td><td>CC ≤ 2.8</td><td colspan="3">2.8 < CC ≤ 4.5</td><td colspan="2">4.5 < CC ≤ 6.0</td><td colspan="2">6.0 < CC ≤ 7.1</td><td colspan="2">> 7.1</td></tr>
<tr><td>Typical AC unit size by CC (tons of refrigeration)</td><td>2.6
(0.75 RT)</td><td colspan="3">3.5
(1 RT)</td><td colspan="2">5.3
(1.5 RT)</td><td colspan="2">7.0
(2 RT)</td><td colspan="2">10.5
(3 RT)</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td>China</td><td colspan="4">CC ≤ 4.5</td><td colspan="4">4.5 < CC ≤ 7.1</td><td colspan="2">7.1 < CC ≤ 14.0</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td>Japan</td><td colspan="2">CC < 3.2</td><td>3.2 < CC ≤ 4.0</td><td colspan="2">4.0 < CC ≤ 5.0</td><td colspan="2">5.0 < CC ≤ 6.3</td><td>6.3 < CC ≤ 7.1</td><td colspan="2">7.1 < CC ≤ 28.0</td></tr>
<tr><td colspan="11"></td></tr>
<tr><td>South Korea</td><td colspan="3">CC < 4</td><td colspan="6">4 ≤ CC < 10</td><td>10 ≤ CC < 17.5</td></tr>
</table>

According to recent data from the Japan Refrigeration and Air Conditioning Industry Association, global RAC demand—including split and window types—is about 85–91 million units annually. China, Europe, India, Japan, South Korea, and the United States account for about 70% of the demand (JRAIA, 2017). Because model-specific sales data were unavailable, we calculate the product-weighted market share[22] of commercially available models (or highest-efficiency models) by manufacturer in each region, which could be different from the sales-weighted market share. See Appendix A for regional energy-efficiency S&L requirements for ACs.

[22] For example, manufacturer A's product-weighted market share is calculated by dividing the total number of manufacturer A's models by the total number of all manufacturers' models in the data set.

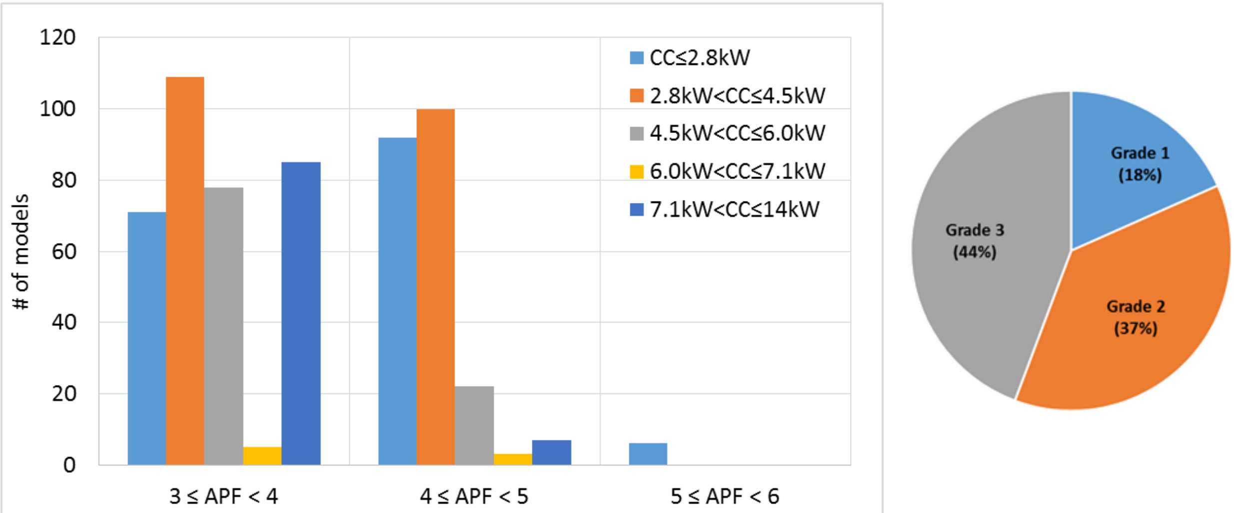
4.1. China

China has the largest RAC market in the world, with domestic sales in China accounting for about 43%–47% of the global RAC market (JRAIA, 2017). The market share of variable-speed inverter RACs increased from 7% in 2007 to over 60% in 2016 (Li et al., 2016; JARN, 2017b). Chinese manufacturers also started selling R-32 RACs in China and exporting to Australia, Southeast Asia, and Europe (JARN, 2017b). Top-tier Chinese manufacturers (e.g., Gree, Midea, and Haier) have also developed R-290 RACs and completed retrofits of production lines[23] for them with support of the United Nations Montreal Protocol Multilateral Fund Demonstration Project. However, there are no or few R-290 RACs commercially available on the market, except for some installed units for demonstration only. (JARN, 2016a, 2015).

In China, minimum energy performance standards (MEPS) were introduced for fixed-speed RACs in 1989 and revised in 2004 (effective from 2005 on) and 2010 (effective from 2010 on). MEPS and labeling requirements for variable-speed units were introduced separately in 2008 and revised in 2013 (Baillargeon et al., 2011; Li et al., 2016; Fridley et al., 2016). The Chinese AC efficiency metrics for variable-speed ACs are a SEER for cooling-only products and annual performance factor (APF) for reversible-type products (i.e., heat pumps). Those are defined by the Chinese AC efficiency standard GB 21455-2013. Both China's SEER and APF are consistent with the cooling seasonal performance factor (CSPF) and the APF defined by ISO 16358, but they use a China-specific outdoor temperature profile. The Chinese efficiency metric for fixed-speed ACs is the EER, CC over power consumption at full-load, defined by the Chinese AC efficiency standard GB 12021.3-2010 and consistent with the definition of ISO 5151.

We obtained data from the LBNL IDEA on 2,024 AC models in China. Of these, we identified 578 split variable-speed reversible-type AC models for which information is available on capacity, efficiency, refrigerant, and price. Figure 1 shows the AC model data by CC and efficiency. The product-weighted average APF and CC of the select models are 3.9 and 4.1 kW, respectively. Nearly all selected products use R-410A refrigerant. The efficiency of the six models that use the low-GWP refrigerant R-32 is low, ranging from APF 3.2 to 3.7, compared to the full efficiency range of APF 3.1 to 5.4, leading to the finding that at least in China, low-GWP R-32 refrigerant is being used even with lower efficiency technology. The most stringent labels, i.e., Grade 1 requirements (see Table A2 in Appendix A), are met by 18% of the models. Figures 2 and 3 show the data by manufacturer. Although Chinese manufacturers (such as Haier, Midea, Gree, Aux, Chigo, and Changhong) account for more than 60% of the total 2,024 models, five manufacturers (Haier, Midea, and Gree headquartered in China, and Mitsubishi and Daikin headquartered in Japan) represent approximately 62% of the 578 variable-speed models selected.

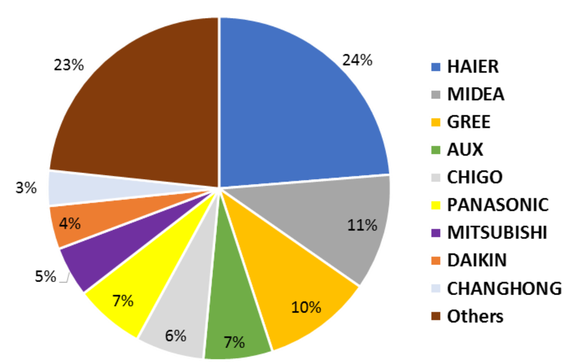
[23] As of the end of 2015, China's RAC industry completed a total of 19 production lines of R-290 RACs and transformed four production lines of R-290 compressors (JARN, 2017g).



- Total 578 models (reversible-type, variable-speed) available in 2016
- Number of manufacturers: 22
- Product-weighted average APF: 3.9
- Product-weighted average CC: 4.1 kW
- R-32 (6 models, APF 3.2–3.7), R-410A (572 models, APF 3.1–5.4)

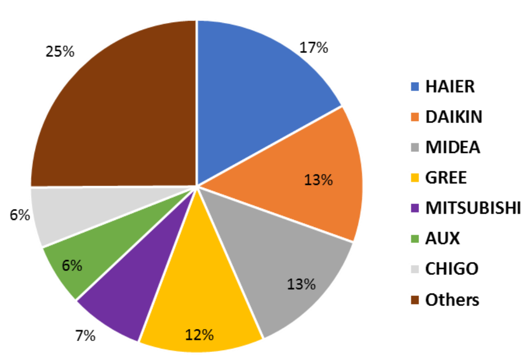
Grade 1 is the most stringent label (see Table A2 in Appendix A).
Source: LBNL IDEA

Figure 1. Distribution of variable-speed RAC models in China in 2016, by efficiency and CC



Source: LBNL IDEA

Figure 2. AC model share, by manufacturer in 2016 (2,024 models)



Source: LBNL IDEA

Figure 3. Share of variable-speed AC models by manufacturer in 2016 (578 models)

The data from the LBNL IDEA represent RACs being sold on the market at the time of data collection, constituting a portion of the AC models registered to the CNIS S&L program database. Although the efficiency of six R-32 models identified by the LBNL IDEA is low, R-32 RACs are not necessarily technically less efficient than R-410A RACs. We also reviewed the Top Runner Program-listed RAC products and low-GWP ACs registered in the S&L program database. A total of 45 models (15 models for three product categories) provided by Gree, Haier, Leader (another brand of the Haier Group), and Changhong were announced in March 2016. The highest-efficiency

RAC models are five models manufactured by Gree that use R-32 refrigerant and one model manufactured by Haier that uses R-410A, which all have APF 4.8 (MIIT, 2016). In December 2016 and January 2017, R-32 RAC models that are more efficient (at an APF of 5.2) than the Top Runner listed models were newly registered to the S&L program database.

Table 4 lists the highest-efficiency RACs we identified in China by product category from all sources listed in Section 3. If the highest-efficiency model uses a high-GWP refrigerant, but there are high-efficiency models that use a low-GWP refrigerant, we include the low-GWP models as well. The most efficient Mitsubishi model MSZ-ZHJ09VA (APF 5.45) is 21% more efficient than the most stringent label threshold, APF 4.5. Highest-efficiency (i.e., highest-APF) ACs are found in the 0.75-RT product category with CCs of 2.8 kW or less. Although the most efficient Mitsubishi model MSZ-ZHJ09VA is not listed in Topten China, other models in that family (MSZ-PZHJ09VA, MSZ-AHJ09VA, and MSZ-ZFJ09VA) are listed. For the 1.0 RT and 1.5 RT categories, Midea's recent R-32 models are the most efficient models identified from the CNIS database.

Table 4. Highest-efficiency RACs in China (CC 0.75–2 RT)

RT	Manufacturer	Model Name	Heat Pump?	CC (kW)	Seasonal Efficiency	Refrigerant	Price[a] (USD)
0.75	Mitsubishi	MSZ-ZHJ09VA; PZHJ09VA	Yes	2.5	China APF 5.45	R-410A	1,134
	Midea	KFR-26GW/BP3DN8Y-YA101(B1)[b]	Yes	2.6	China APF 5.2	R-32	627
1.0	Midea	KFR-35GW/ BP3DN8Y-YA101(B1)[c]	Yes	3.5	China APF 5.05	R-32	729
1.5	Midea	KFR-51LW/ BP3DN8Y-YB200(B1)[d]	Yes	5.1	China APF 4.51	R-32	1,339
2.0	Daikin	FVXF172NC-W	Yes	7.2	China APF 4.43	R-410A	2,215
	Midea	KFR-72LW/ BP3DN8Y-YB200(B1)[e]	Yes	7.2	China APF 4.15	R-32	1,499

[a] 1 U.S. dollar (USD) = 6.72 Yuan
[b] Similar models (China APF 5.2) registered to the CNIS database: KFR-26GW/BP3DN8Y-YA100(B1); YA201(B1); - TA201(B1); -TA100(B1); - DA100(B1); -DA200(B1)
[c] Similar models (China APF 5.05) registered to the CNIS database: KFR-35GW/BP3DN8Y-YA100(B1); YA201(B1); -TA201(B1); -TA100(B1); - DA100(B1); -DA200(B1)
[d] Similar models (China APF 4.51) registered to the CNIS database: KFR-51LW/BP3DN8Y-YA100(B1); -YB201(B1); -YA201(B1);-YA200(B1); -YB300(B1); -YB301(B1)
[e] Similar models (China APF 4.15) registered to the CNIS database: KFR-72LW/BP3DN8Y-YA200(B1); -YA201(B1); -YB201(B1); -YB300(B1); -YB301(B1)
Source: LBNL IDEA, CNIS database, Topten China, Top Runner China, and web searches

Table 5 summarizes key characteristics of the Chinese RAC market.

Table 5. Summary of RAC market, S&L, and low-GWP refrigerants in China

<table>
<tr><td>Annual RAC demand</td><td>41.4 million (2011), 38.4 million (2016)</td></tr>
<tr><td>Market share of variable-speed RACs</td><td>Over 60% of RACs sold in 2016</td></tr>
<tr><td>S&L vs. Highest-efficiency and BAT low-GWP RACs</td><td>
<table>
<tr><td>Type</td><td>MEPS</td><td>Most stringent label</td><td rowspan="2">Highest-efficiency RAC</td><td rowspan="2">BAT low-GWP RAC</td></tr>
<tr><td rowspan="2">Variable-speed (reversible)</td><td colspan="2">For ACs with CC ≤ 4.5 kW</td></tr>
<tr><td>China APF 3.5</td><td>China APF 4.5 (Grade 1)</td><td>APF 5.45 (R-410A)</td><td>APF 5.2 (R-32)</td></tr>
</table>
</td></tr>
<tr><td>Dominant refrigerants in RACs</td><td>R-22 (for fixed-speed units), R-410A (for variable-speed units)</td></tr>
<tr><td>Low-GWP RACs</td><td>R-32 available on the market, including highly efficient R-32 models.
R-290 not available yet on the market, but Chinese manufacturers have completed retrofits of production lines for R-290 RACs.</td></tr>
<tr><td>Leading manufacturers</td><td>Haier, Midea, Gree, Aux, Chico, and Changhong (headquartered in China); Daikin, Mitsubishi, and Panasonic (headquartered in Japan)</td></tr>
</table>

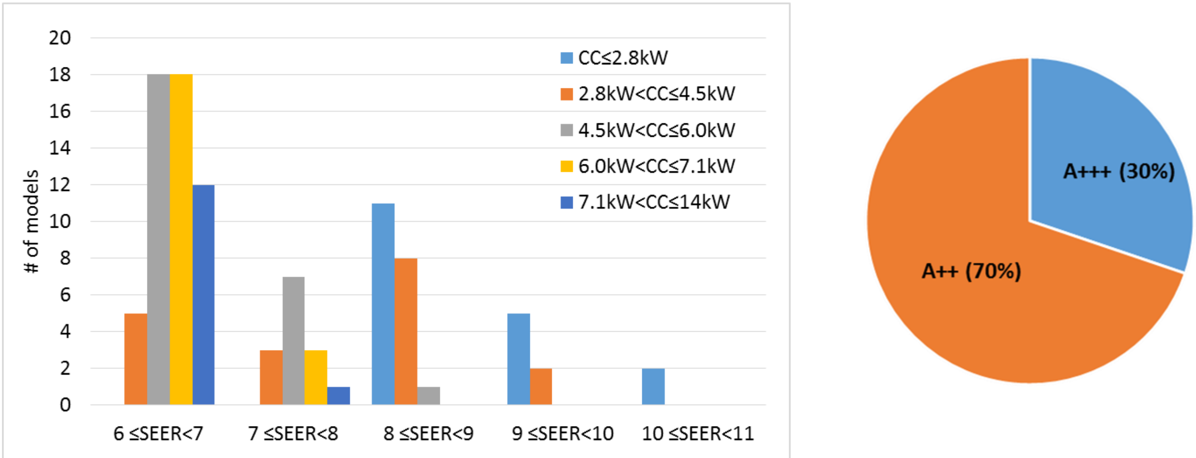
4.2. Europe

European countries account for about 5.5%–8% of the global RAC market, and five countries (Russia, Italy, Turkey, Spain, and France) account for more than 65% of the European total (JARN, 2017c; JRAIA, 2017). Japanese manufacturers (Daikin, Mitsubishi Electric, Panasonic, and Fujitsu General) and South Korean manufacturers (Samsung and LG) lead the market. Variable-speed RACs already accounted for 55%–75% of RAC sales in 2007 (Topten EU, 2012). Although R-410A RACs are still dominant in the region, R-32 RACs produced by Japanese manufacturers have become more available on the market, especially in high-end models in the A+++ energy efficiency class[24] (JARN, 2017c). R-290, provided mainly by Chinese manufacturers, is used mostly for portable ACs.

In the EU, energy labels help consumers choose energy-efficient products, and Eco-design regulations require manufacturers to decrease the energy consumption of their products by establishing MEPS. The Eco-design Directive (for ACs with ≤ 12 kW CC) requires different levels of efficiency by refrigerant GWP and capacity. The European efficiency metric for ACs is a SEER for cooling performance and a seasonal coefficient of performance (SCOP) for heating performance, defined by the European Commission using the region-specific temperature profiles (Schleicher, 2013).

We obtained a data set of the 96 highest-efficiency models with A+++ and A++ energy-efficiency classes from the Topten EU website. Figure 4 shows the RAC model data by CC and efficiency. The product-weighted average SEER and CC of the select models are 7.3 and 5.4 kW, respectively. Figure 5 shows the data by manufacturer. Five manufacturers (Daikin, Mitsubishi, Samsung, Toshiba, and Hitachi) based in Japan and South Korea produce 85% of the 96 models. Figure 6 shows the data by refrigerant type. Nearly all products use R-410A. Four models that use low-GWP R-32 have very high efficiency, ranging from SEER 8.6 to 10.5.

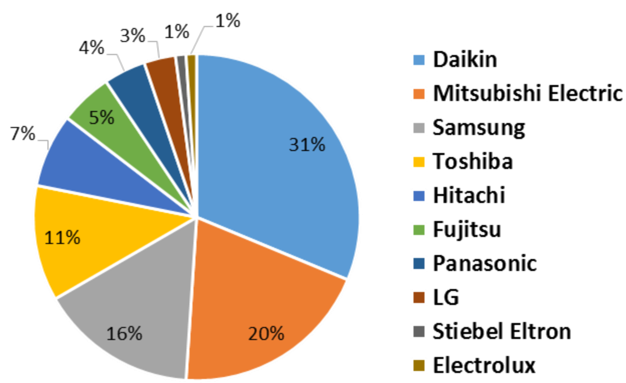
[24] A+++ is the most stringent label in the EU. See Table A3 in Appendix A.



- Total 96 models (reversible type) available in 2016
- Number of manufacturers: 10
- Product-weighted average SEER: 7.3
- Product-weighted average CC: 5.4 kW
- R-32 (4 models, SEER 8.6–10.5), R-410A (82 models, SEER 6.1–10.1), unspecified (10 models)

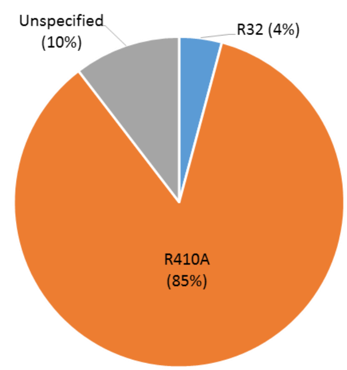
Source: Topten EU

Figure 4. Distribution of highest-efficiency RAC models in Europe in 2016, by efficiency and CC



Source: Topten EU

Figure 5. Share of energy-efficient AC models in Europe, by manufacturer (96 models)



Source: Topten EU

Figure 6. Share of energy-efficient AC models in Europe, by refrigerant type (96 models)

Table 6 lists the highest-efficiency RACs in Europe. The most efficient (i.e., highest EU SEER) RACs are found in the 0.75-RT product category with a CC of 2.8 kW or less. RAC models provided by global manufacturers based in South Korea and Japan lead high-efficiency RACs in Europe. The highest-efficiency Panasonic CS-VZ9SKE/CU-VZ9SKE and Daikin FTXZ-N/RXZ-N series models use low-GWP R-32 refrigerant; other energy-efficient models employ R-410A. Although Panasonic's CS-VZ12SKE/CU-VZ12SKE is not listed on the Topten EU website, we found information on that model through web searches. This model also has very high efficiency, with a declared SEER of 10.0. This is higher than the efficiency of Samsung model

AR12HSSDAWKNEU/AR12HSSDAWKX, which Topten EU claims is the most efficient model in the 1.0-RT product category.

Table 6. Highest-efficiency RACs in Europe (CC 0.75–2 RT)

RT	Manufacturer	Model Name	Heat pump?	CC (kW)	Seasonal Efficiency	Refrigerant	Price[a] (USD)
0.75	Panasonic	CS-VZ9SKE/CU-VZ9SKE	Yes	2.5	EU SEER 10.5	R-32	2,168
1.0	Panasonic	CS-VZ12SKE/CU-VZ12SKE	Yes	3.5	EU SEER 10.0	R-32	2,479
1.5	Daikin	FTXZ50N/RXZ50N	Yes	5.0	EU SEER 8.6	R-32	2,906
2.0	Mitsubishi	MSZ-GF71VE/MUZ-GF71VE	Yes	7.1	EU SEER 6.8	R-410A	2,071

[a] 1 USD = 0.76 British Pound; 1 USD = 0.84 EURO
Source: Topten EU and web searches

Table 7 shows a summary of the collected data for Europe.

Table 7. Summary of RAC market, S&L, and low-GWP refrigerants in Europe

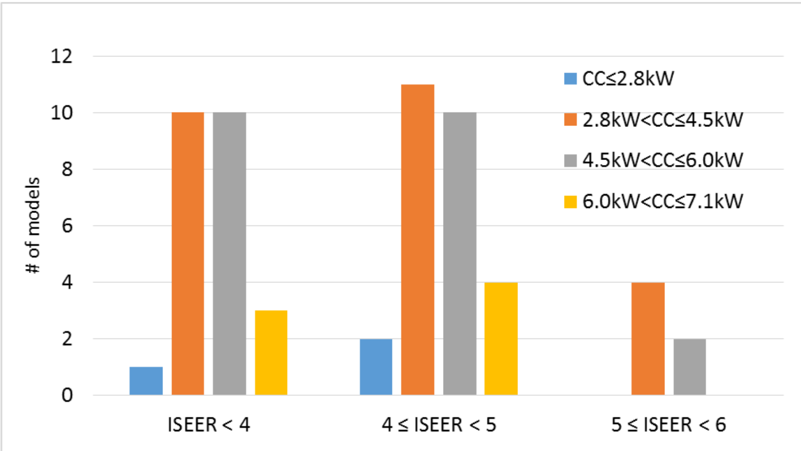
<table>
<tr><td>Annual RAC demand</td><td colspan="5">7.0 million (2011), 5.4 million (2016)
(Russia, Italy, Turkey, Spain, and France represent more than 65% of the European market.)</td></tr>
<tr><td>Market share of variable-speed RACs</td><td colspan="5">55%–75% of sales in 2007 (EU)</td></tr>
<tr><td rowspan="2">S&L vs. Highest-efficiency and BAT low-GWP RACs (EU)</td><td>Type</td><td>MEPS</td><td>Most stringent label</td><td>Highest-efficiency RAC</td><td>BAT low-GWP RAC</td></tr>
<tr><td>Ductless split</td><td>EU SEER 4.60
(GWP > 150 for < 6 kW)
EU SEER 4.14
(GWP ≤ 150 for < 6 kW)</td><td>EU SEER 8.5
(A+++)</td><td>EU SEER 10.5
(R-32)</td><td>EU SEER 10.5
(R-32)</td></tr>
<tr><td>Dominant refrigerants in RACs</td><td colspan="5">R-410A</td></tr>
<tr><td>Low-GWP RACs</td><td colspan="5">R-32 available on the market (mainly in high-end models)
R-290 available on the market (mainly in portable ACs)</td></tr>
<tr><td>Leading manufacturers</td><td colspan="5">Daikin, Mitsubishi Electric, Panasonic, and Fujitsu General (headquartered in Japan); Samsung and LG (headquartered in South Korea)</td></tr>
</table>

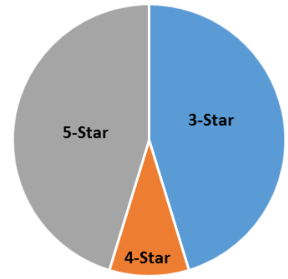
4.3. India

India accounts for about 28%–30% of the Asian (excluding China and Japan) RAC market and 4%–5% of the global market (JRAIA, 2017). In India, variable-speed ACs that account for about 10% of wall-mounted split AC products are the fastest-growing category, achieving a 41% growth rate in sales between 2015 and 2016 (JARN, 2017i). R-22 is still the dominant refrigerant for fixed-speed ACs in the market. However, Japanese manufacturers and a few Indian manufacturers are launching R-32 RAC models. Godrej uses R-290 for its models in 1-RT and 1.5-RT products, accounting for about 40% of its sales and resulting in cumulative sales of 120,000 units through the end of 2016 (JARN, 2017i).

The BEE launched a voluntary S&L program in May 2006 with an overarching agenda to reduce the energy intensity of electrical appliances. The labels use a comparative five-star rating system based on annual or daily energy consumption (Abhyankar et al., 2017). In 2012, mandatory labeling was introduced for split and window fixed-speed RACs. In June 2015, the BEE adopted a voluntary label for inverter ACs with a one-star level of 3.1 and a five-star level of 4.5, using the newly adopted Indian SEER (ISEER) metric. The ISEER is consistent with the CSPF defined by ISO 16358 using an India-specific temperature profile, except that the ISEER calculation does not consider performance at minimum-load operation (Abhyankar et al., 2017).

We obtained two data sets from the LBNL IDEA, which collected comprehensive data on ACs available on the market, as well as Bijli Bachao, where information on India's top 10 most-efficient ACs is available. Figure 7 shows the data for the selected 57 energy-efficient RAC models by CC and efficiency. Highest-efficiency (i.e., highest ISEER) RACs in India are in the 1-RT product category. The efficiency of six models is ISEER 5 or higher. Figures 8 and 9 show the data by manufacturer. There are more than 20 competitors in the Indian RAC market, including Indian, Japanese, South Korean, and Chinese manufacturers. Hitachi, Blue Star, Daikin, and LG account for 36% of the total 785 models identified from the IDEA, and they account for 71% of the energy-efficient 57 models.

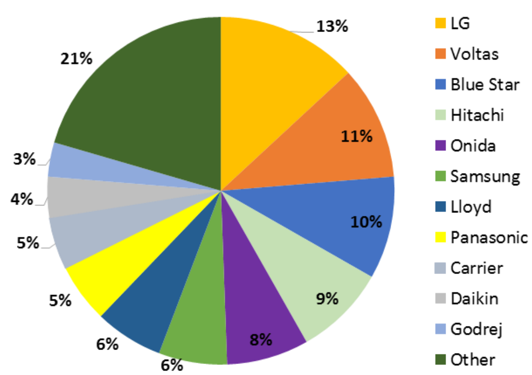




- Total 57 models available in 2016–2017
- Number of manufacturers: 9
- Product-weighted average ISEER: 4.35
- Product-weighted average CC: 4.6 kW
- R-32 (9 models), R-290 (5 models), R-410A (43 models)

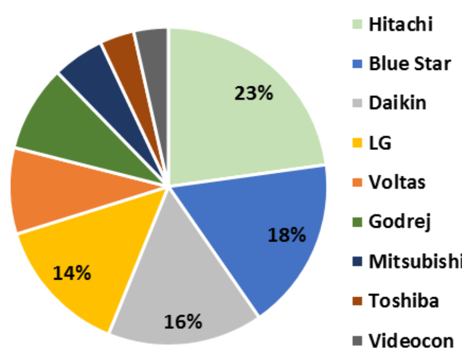
Source: LBNL IDEA and Bijli Bachao

Figure 7. Distribution of energy-efficient RAC models in India in 2016–2017, by efficiency and CC



Source: LBNL IDEA and Bijli Bachao

Figure 8. Share of AC models in India, by manufacturer (785 models)



Source: LBNL IDEA and Bijli Bachao

Figure 9. Share of energy-efficient AC models in India, by manufacturer (57 models)

Table 8 lists the highest-efficiency (i.e., highest ISEER) RACs. Hitachi's Kashikoi series (including RAU512CWEA, RSA518CAEA, and RMA524CAEA), which uses R-410A, had the highest-efficiency ACs through the end of 2016. In March 2017, Daikin and Godrej both announced ACs (using R-32 and R-290, respectively) that achieve ISEER 5.8. (Abhyankar et al, 2017).

Table 8. Highest-efficiency RACs in India (CC 1–2 RT)

RT	Manufacturer	Model Name	Heat pump?	CC (kW)	Seasonal Efficiency	Refrigerant	Price[a] (USD)
1.0	Daikin	JTKM35SRV16	No	3.6	ISEER 5.8	R-32	718
	Godrej	GSC 12 FIXH 7 GGPG[b]	No	3.5	ISEER 5.8	R-290	905
	Hitachi	RAU512AWEA	No	3.6	ISEER 5.75	R-410A	916
1.5	Daikin	JTKM50SRV16	No	5.0	ISEER 5.2	R-32	819
2.0	Mitsubishi	MSY-GK24VA	No	6.7	ISEER 4.8	R-410A	936

[a] 1 USD = 64 Indian Rupee
[b] On March 7, 2017, Godrej announced the launch of a new inverter RAC with ISEER 5.8. The previous version is GSC 12 GIG 5 DGOG with ISEER 5.2.
Source: LBNL IDEA, Bijli Bachao, and web searches

Table 9 shows a summary of the collected data for India.

Table 9. Summary of RAC market, S&L, and low-GWP refrigerants in India [25]

<table>
<tr><td>Annual RAC demand</td><td>3.4 million (2011), 4.3 million (2016)</td></tr>
<tr><td>Market share of variable-speed RACs</td><td>~10% of RACs sold in 2016</td></tr>
<tr><td>S&L vs. Highest-efficiency and BAT low-GWP RACs</td><td><table><tr><td>Type</td><td>MEPS</td><td>Most stringent label</td><td>Highest-efficiency RACs</td><td>BAT low-GWP RACs</td></tr><tr><td>RAC</td><td>ISEER 3.1</td><td>ISEER 4.5
(5 Stars)</td><td>ISEER 5.8
(R-32, R-290)</td><td>ISEER 5.8
(R-32, R-290)</td></tr></table></td></tr>
<tr><td>Dominant refrigerants in RACs</td><td>R-22 (mainly because fixed-speed units are still dominant on the market)</td></tr>
<tr><td>Low-GWP RACs</td><td>R-32 available on the market (led by Japanese manufacturers)
R-290 available on the market (led by Godrej)</td></tr>
<tr><td>Leading manufacturers</td><td>Daikin, Hitachi, Panasonic, Voltas, Blue Star, Godrej, LG, Samsung</td></tr>
</table>

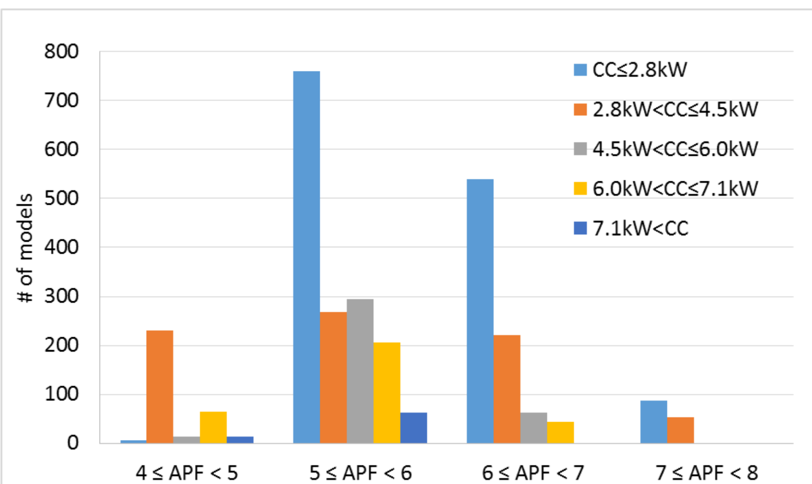
[25] For more details on the bulk procurement process in India, see Abhyankar et al. (2017).

4.4. Japan

Japan accounts for about 9%–10% of the global RAC market (JARN, 2017d; JRAIA, 2017). According to the ECCJ database, all RACs sold in Japan are reversible type, i.e., heat pumps. Japanese manufacturers have been investing in research and development on alternative AC refrigerants. Nearly all RAC products recently available in the market use R-32 refrigerant since Daikin launched the first R-32 RACs in 2012.

Although mandatory energy-efficiency standards for appliances and automobiles had been in effect since 1980, in 1998 the Top Runner approach was adopted in the revision of the Energy Conservation Law as a new method for setting energy-efficiency targets, which play a role as MEPS, for selected products (Kimura, 2010). The most efficient product on the market during the standard-setting process sets the Top Runner standards (see Abhyankar et al. (2017) for an example of accelerated AC efficiency improvement driven by such an energy efficiency policy). The Japanese efficiency metric for ACs is APF, which is based on both CSPF and heating seasonal performance factor (HSPF). This is defined by Japanese Industrial Standards Committee standard 9312 and is consistent with ISO 16358 but with a Japan-specific temperature bin.

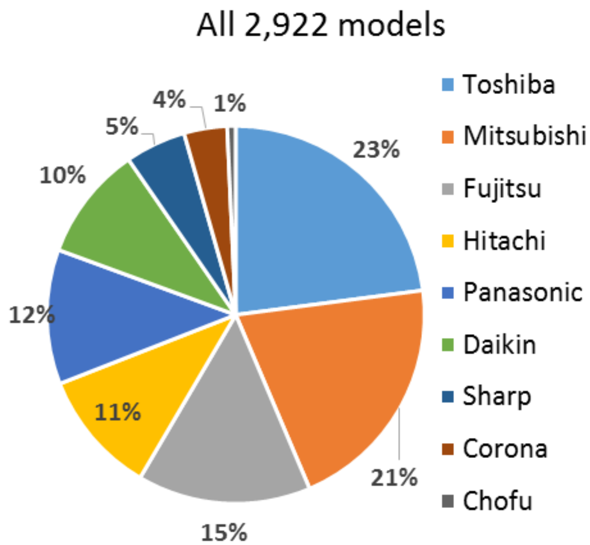
We obtained a data set of 2,922 models (registered between October 2006 and September 2016) from the ECCJ database. Of these, 1,570 were registered between 2014 and 2016. Figure 10 shows the AC model data by CC and efficiency. The product-weighted average APF and CC of the select models are 5.8 and 3.9 kW, respectively. Figures 11 and 12 show the data by manufacturer. Seven manufacturers (Daikin, Fujitsu, Hitachi, Mitsubishi, Panasonic, Toshiba, and Sharp) produce 95% of the 2,922 models, and 100% of the 139 models with APF ≥ 7.



- Total 2,922 models (reversible type) registered between October 2006 and September 2016
- Number of manufacturers: 10
- Product-weighted average APF: 5.8
- Product-weighted average CC: 3.9 kW

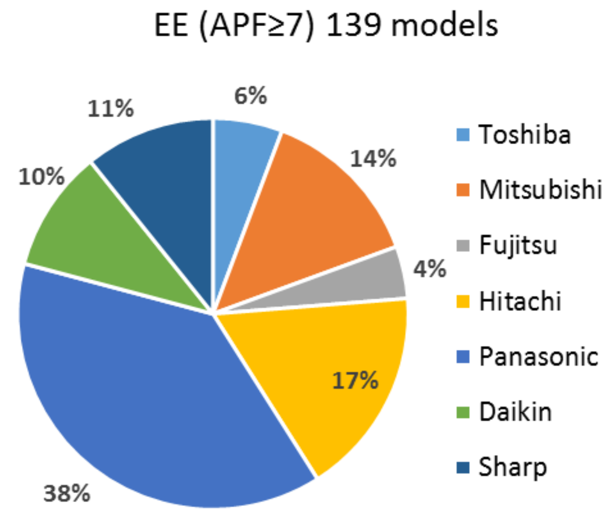
Source: ECCJ database

Figure 10. Distribution of RAC models in Japan, by efficiency and CC



Source: ECCJ database

Figure 11. Share of AC models in Japan, by manufacturer (2,922 models)



Source: ECCJ database

Figure 12. Share of energy-efficient AC models (APF ≥ 7) in Japan, by manufacturer (139 models)

Table 10 shows the highest-efficiency RAC models by product category. The highest-efficiency (i.e., highest-APF) RACs are found in the 0.75 RT and 1 RT (4.5 kW or less) product categories. The efficiency (APF 7.6) of those models is 26% higher than the Top Runner standard.

Table 10. Highest-efficiency RACs in Japan (CC 0.75–2 RT)

RT	Manufacturer	Model Name	Heat pump?	CC (kW)	Seasonal Efficiency	Refrigerant	Price[a] (USD)
0.75	Hitachi	RAS-X25G	Yes	2.5	Japan APF 7.6	R-32	2,232
1.0	Panasonic	CS-WX407C2	Yes	4.0	Japan APF 7.6	R-32	3,087
	Hitachi	RAS-X40G2[b]	Yes	4.0	Japan APF 7.6	R-32	2,502
1.5	Mitsubishi	MSZ-FZ5617S	Yes	5.6	Japan APF 6.8	R-32	2,735
2.0	Mitsubishi	MSZ-FZ7117S	Yes	7.1	Japan APF 6.3	R-32	2,200

[a] 1 USD = 110 Japanese Yen

[b] This model is a “dimension-defined” type, i.e., an indoor device that is less than 800 mm in width and 295 mm in height. Other types are categorized as “dimension-free.” In Japan, the target APF for dimension-defined types is less than that for dimension-free types.

Source: ECCJ database and web searches

Table 11 shows a summary of the collected data for Japan.

Table 11. Summary of RAC market, S&L, and low-GWP refrigerants in Japan

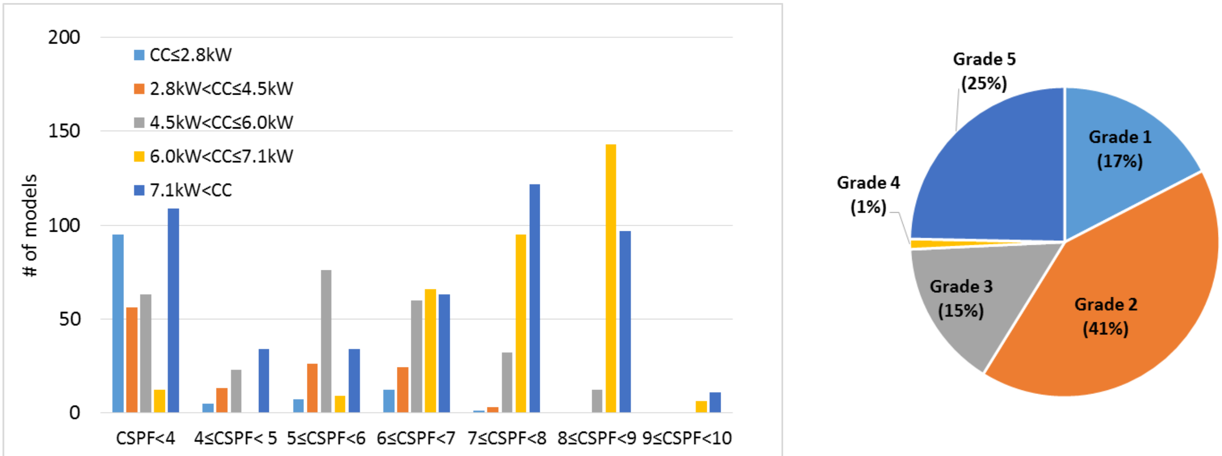
<table>
<tr><td>Annual RAC demand</td><td>8.3 million (2011), 8.4 million (2016)</td></tr>
<tr><td>Market share of variable-speed RACs</td><td>100% in new sales</td></tr>
<tr><td>S&L vs. Highest-efficiency and BAT low-GWP RACs</td><td>
<table>
<tr><td>Type</td><td>Top Runner standards</td><td>Highest-efficiency RACs</td><td>BAT low-GWP RACs</td></tr>
<tr><td>Ductless split wall-mounted</td><td>For RACs with CC < 3.2 kW, APF 5.8 (dimension-defined type) or APF 6.0 (dimension-free type)</td><td>Japan APF 7.6 (R-32)</td><td>Japan APF 7.6 (R-32)</td></tr>
</table>
Top Runner standards in Japan serve as MEPS.</td></tr>
<tr><td>Dominant refrigerants in RACs</td><td>R-32</td></tr>
<tr><td>Low-GWP RACs</td><td>R-32 available on the market</td></tr>
<tr><td>Leading manufacturers</td><td>Daikin, Fujitsu, Hitachi, Mitsubishi, Panasonic, Sharp, and Toshiba</td></tr>
</table>

4.5. South Korea (Republic of Korea)

Although South Korea accounts for less than 1% of the global RAC market (JRAIA, 2017), two South Korean manufacturers, Samsung and LG, are leading RAC sellers in the global market and dominate the South Korean market. The estimated share of variable-speed RACs in South Korea increased from less than 10% in 2008 to about 90% in 2015 (Abhyankar et al., 2017). Cooling-only products are more popular than reversible-type products (i.e., heat pumps) in South Korea. The use of flammable refrigerants in RACs is restricted in the country. However, mildly flammable low-GWP refrigerants such as R-32 likely will be allowed for RAC use in the near future (KRAAC, 2017).

The South Korean government has been running the Energy-Efficiency Label and Standard Program since 1992 with the aim of improving the energy efficiency of key products, including appliances and vehicles that account for most energy consumption (Abhyankar et al., 2017; McNeil et al., 2012). Mandatory MEPS were established in 2002 and took effect in 2004 for window and split ACs up to 23 kW CC. In September 2011, the government announced the Energy Frontier program, which sets mid-term energy-efficiency goals for key appliances, including RACs, at 30%–50% more efficient than Grade 1 (most efficient) (Abhyankar et al., 2017; McNeil et al., 2012). The South Korean efficiency metric for ACs refers to CSPF for cooling-only products and the average of CSPF and HSPF for reversible-type products defined by the Korea Standard C9306, which is largely consistent with ISO 16358 but uses a Korea-specific outdoor temperature profile and some adjustments.

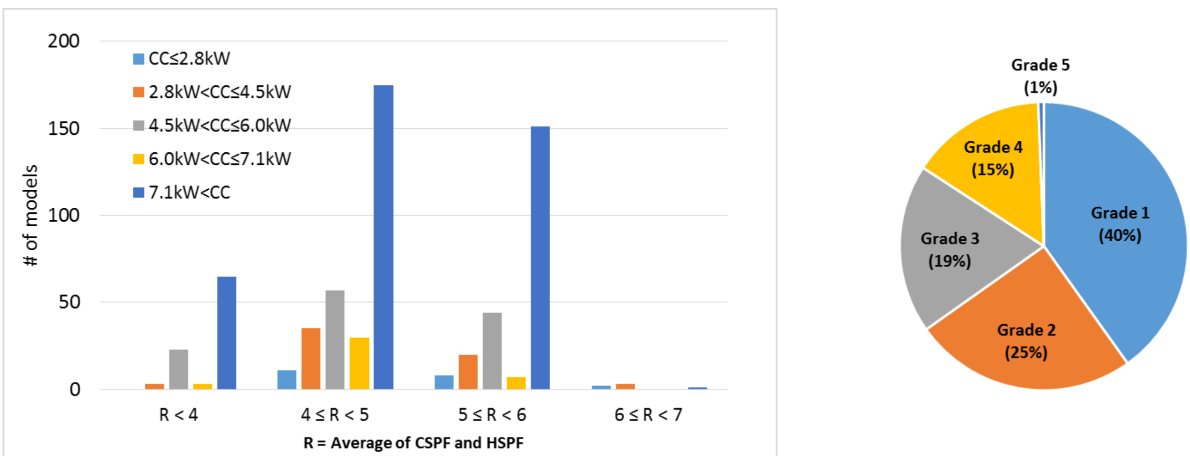
We obtained a data set of 1,947 models (1,309 cooling-only models and 648 reversible-type models, i.e., heat pumps, registered between January 2013 and November 2016) from the database of KEA, which has been implementing South Korea's energy-efficiency S&L program. Figure 13 and 14 show the 1,309 cooling-only AC model data and the 638 reversible-type AC model data, respectively, by CC and efficiency. The product-weighted average CSPF and CC of the cooling-only models are 6.0 and 6.5 kW, respectively. 17% of the cooling-only models and 40% of the reversible-type models meets grade 1 levels. The product-weighted average efficiency (R = average of CSPF and HSPF) and CC of the reversible-type models are 4.8 and 8.8 kW, respectively. Figures 15 and 16 show the data by brand. LG, Samsung, and Carrier produce 87% of the 1,309 cooling-only models and 95% of the 638 reversible-type models.



- Total 1,309 models (cooling-only type) registered between January 2013 and November 2016
- Number of manufacturers: 18
- Product-weighted average CSPF: 6.0
- Product-weighted average CC: 6.5 kW

Source: KEA database

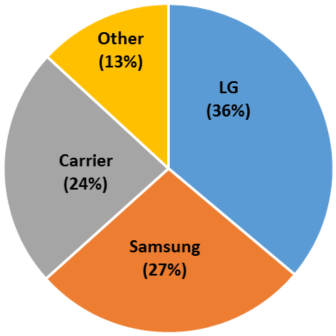
Figure 13. Distribution of RAC models (cooling-only type) in South Korea, by efficiency and CC



- Total 638 models (reversible type) registered between January 2013 and November 2016
- Number of manufacturers: 14
- Product-weighted average efficiency (R = average of CSPF and HSPF): 4.8
- Product-weighted average CC: 8.8 kW

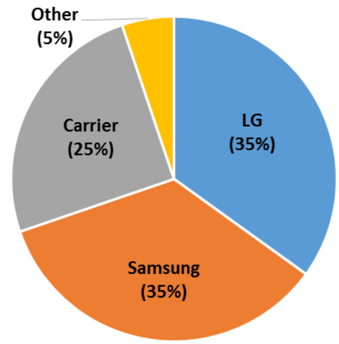
Source: KEA database

Figure 14. Distribution of RAC models (reversible type) in South Korea, by efficiency and CC



Source: KEA database

Figure 15. Share of AC models in South Korea, by manufacturer (1,309 models, cooling-only type)



Source: KEA database

Figure 16. Share of AC models in South Korea, by manufacturer (638 models, reversible type)

Cooling-only RACs are still dominant in South Korea. Highest-efficiency (i.e., highest-CSPF) RACs in cooling-only products are available in the 2 RT product category, with CC ranging from 6.5 to 7.2 kW (see Figure 13 and Table 12). Most of the RACs in this category are floor-standing types.

Table 12. Highest-efficiency RACs (cooling-only type) in South Korea (CC 0.75–2 RT)

RT	Manufacturer	Model Name	Heat pump?	CC (kW)	Seasonal Efficiency	Refrigerant	Price[a] (USD)
0.75	Samsung	AR06HVAF1WK	No	2.3	Korea CSPF 7.1	R-410A	658
1.0	LG	SNQ111BSF1W/ SUQ111SAF	No	4.2	Korea CSPF 7.8	R-410A	739
1.5	LG	SNQ131BMF1W/ SUQ131MAF	No	5.2	Korea CSPF 8.0	R-410A	N/A[c]
2.0	Carrier	AMC16VX1PS10[b]	No	6.5	Korea CSPF 9.7	R-410A	N/A[c]
	Samsung	AF18J9975WWK[b]	No	7.2	Korea CSPF 9.6	R-410A	2,730

[a] 1 USD = 1,120 Korean Won
[b] Floor-standing type (all other models are wall-mounted type)
[c] Price information not available at time of study
Source: KEA database (efficiency) and web searches (price)

Table 13 shows a summary of the collected data for South Korea.

Table 13. Summary of RAC market, S&L, and low-GWP refrigerants in South Korea

<table>
<tr><td>Annual RAC sales</td><td colspan="5">8.2 million (2010), 8.8 million (2016)</td></tr>
<tr><td>Market share of variable-speed RACs</td><td colspan="5">~90% of RACs sold in 2015</td></tr>
<tr><td rowspan="3">S&L vs. Highest-efficiency and BAT low-GWP RACs</td><td>Type</td><td>MEPS</td><td>Most stringent label</td><td>Highest-efficiency RAC</td><td>BAT low-GWP RAC</td></tr>
<tr><td rowspan="2">Split ACs</td><td colspan="2">For ACs with 4 kW ≤ CC < 10 kW</td><td rowspan="2">CSPF 9.7 (R-410A)</td><td rowspan="2">Not available</td></tr>
<tr><td>2.97</td><td>9.36 (Energy Frontier)
7.20 (Grade 1)</td></tr>
<tr><td>Dominant refrigerants in RACs</td><td colspan="5">R-410A (variable-speed units), R-22 (fixed-speed units)</td></tr>
<tr><td>Low-GWP RACs</td><td colspan="5">R-32 expected to be available on the market</td></tr>
<tr><td>Leading manufacturers</td><td colspan="5">Samsung, LG, and Carrier</td></tr>
</table>

4.6. United States

Residential ACs in the United States fall into two broad categories: central ACs and room ACs (RACs). Central ACs in the United States include ductless split ACs (mini splits), which are classified as RACs in other countries.. RACs in the United States are defined as consumer products sold as an encased unit for mounting in a window or through the wall (US DOE, 2015a, 2011).

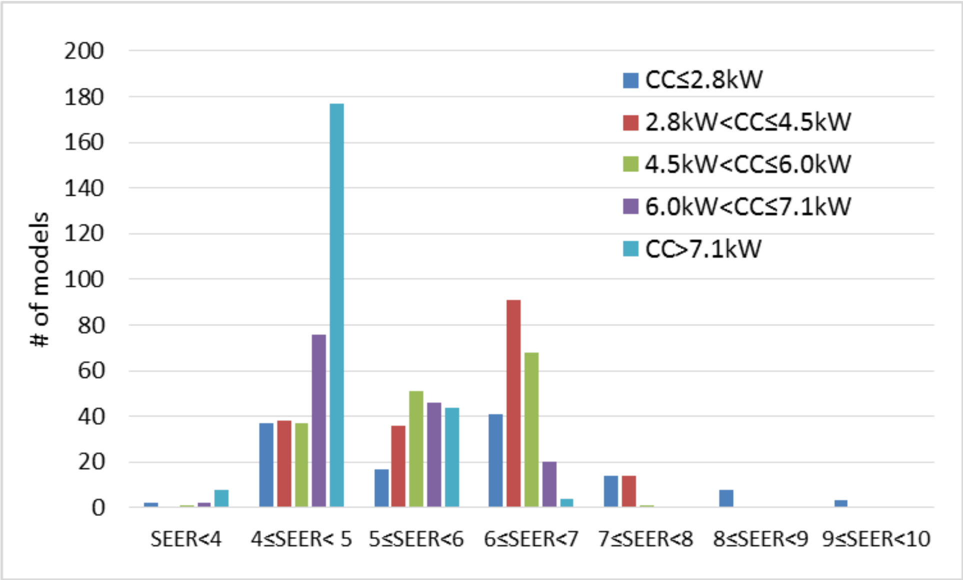
Although the United States accounts for about 10% of the global RAC market that includes window and split types, split ACs represent about 9%–10% (amounting to less than 1 million units annually) of the U.S. RAC demand (JRAIA, 2017). Ductless split AC systems (mini-splits) have a small but gradually increasing market share in the United States, where large ducted air-to-air whole-house AC systems dominate (JARN, 2017e; Goetzler et al., 2016). Approximately 70% of U.S. ACs are cooling-only type (Baillargeon et al., 2011).

The United States has been running an extensive MEPS program for ACs and heat pumps by product type.[26] Although the US DOE revised several times the efficiency standards for central ACs since first implemented in 1992, the latest revision of the standards has adopted regional MEPS by dividing the nation into three regions (North, Southeast, and Southwest) based on the population-weighted number of heating degree days. As a result, split central ACs installed on or after January 1, 2015, must meet MEPS in SEER (both SEER and HSPF for heat pumps) or in both SEER and EER (for the Southwest region) (US DOE, 2015b). The low-GWP, mildly flammable R-32 refrigerant has been approved for self-contained ACs (which does not include mini-splits) with a refrigerant charge volume of less than 7.8 kg.

We obtained a data set of 836 mini-splits (updated in July 2017) from the LBNL IDEA. Figure 17 shows the AC model data by CC and efficiency. For the 836 models, the product-weighted average SEER and CC are 5.4 and 6.2 kW, respectively. More than 95% of the 836 mini-splits are reversible type (i.e., heat pumps), and R-410A is still dominant in this market. Figure 18 shows the share of mini-splits by manufacturer. Seven manufacturers (Mitsubishi, Gree, Daikin, Fujitsu, Panasonic, Carrier, and LG) account for about 80% of the 836 models.[27]

[26] These include residential RACs (window/wall), package terminal ACs (wall units with an air change function included), central ACs and heat pumps, small commercial package ACs and heat pumps, and large commercial package ACs and heat pumps.

[27] According to JARN (2017e), Mitsubishi Electric is leading the U.S. mini-split AC market, accounting for more than 30% by sales.

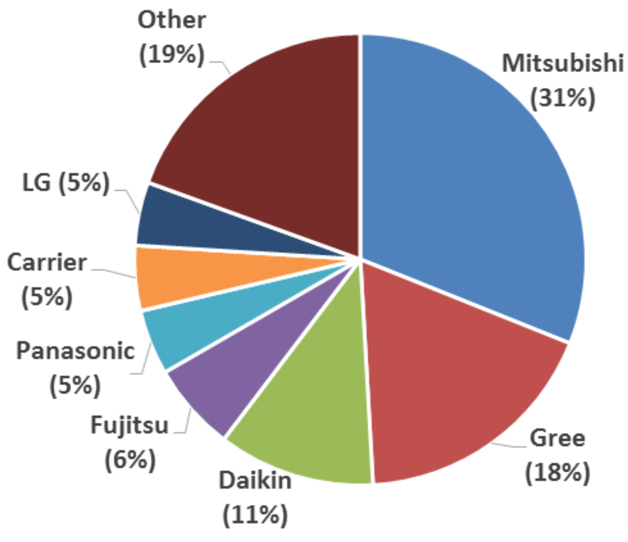


- Total 836 models (mini-splits)
- Number of brands: 33
- Product-weighted average SEER: 5.4
- Product-weighted average CC: 6.2 kW
- R-410A (428 models, SEER 3.8–9.7), unspecified (408 models)

Note that SEER on this figure is expressed in W/W for this study. AC efficiency in the United States is typically expressed in Btu/(W· h). 1 Btu/h is equivalent to 0.293 W.

Source: LBNL IDEA

Figure 17. Distribution of mini-split ACs in the United States in 2017, by efficiency and CC



Source: LBNL IDEA

Figure 18. Share of mini-split models in the United States, by manufacturer (836 models)

We also reviewed 373 split AC models (cooling-only 177 models and reversible-type 196 models), excluding discontinued models, from the CEE Directory of Efficient Equipment and the ENERGY STAR Most Efficient 2017 list (for central ACs and air-source heat pumps). The highest-efficiency model in 2017 has 11.7 (W/W) US SEER in the 0.75-RT category. Gree's models that have US SEER 38 (11.7 W/W) and US SEER 30.5 (8.9 W/W) are sold by TOSOT USA.[28] Table 14 lists the highest-efficiency mini-splits by product category.

Table 14. Highest-efficiency ACs in the United States (mini-splits, CC 0.75–2 RT)

RT	Manufacturer	Model Name	Heat pump?	CC (kW)	Seasonal Efficiency[a]	Refrigerant	Price (USD)
0.75	Gree	SAP09HP230V1BO	Yes	2.6	US SEER 11.7	R-410A	N/A[b]
1.0	Gree	GWH12YD-D3DNA1A/O	Yes	3.5	US SEER 8.9	R-410A	2,339
1.5	Gree	GWH18YE-D3DNA1A/O	Yes	5.3	US SEER 7.2	R-410A	N/A[b]
2.0	LG	LAU240HYV1	Yes	6.4	US SEER 6.4	R-410A	1,485

[a] The unit of SEER is expressed in W/W for this study. AC efficiency in the United States is typically expressed in Btu/(W· h). 1 Btu/h is equivalent to 0.293 W.
[b] Price information not available at time of study
Source: LBNL IDEA, AHRI-CEE Directory, ENERGY STAR, and web searches

Table 15 shows a summary of the collected data for the United States.

Table 15. Summary of RAC market, S&L, and low-GWP refrigerants in the United States

<table>
<tr><td>Annual RAC sales</td><td colspan="5">6.6 million (2011), 7.9 million (2016)
* mini-splits ~0.8 million (2016)</td></tr>
<tr><td rowspan="2">S&L vs. Highest-efficiency RACs (mini-splits)</td><td>Type</td><td>MEPS</td><td>Most stringent label</td><td>Highest-efficiency RACs</td><td>BAT low-GWP RAC</td></tr>
<tr><td>Split heat pumps</td><td>SEER 4.10
HSPF 2.40</td><td>SEER 5.27
HSPF 2.49
EER 3.66</td><td>SEER 11.7
(R-410A)</td><td>Not available</td></tr>
<tr><td>Dominant refrigerants in RACs</td><td colspan="5">R-410A</td></tr>
<tr><td>Low-GWP RACs</td><td colspan="5">R-32 available for self-contained systems (not mini-splits) on the market</td></tr>
<tr><td>Leading manufacturers (mini-splits)</td><td colspan="5">Mitsubishi Electric, Gree, Fujitsu General, Daikin, Carrier, Panasonic, and LG</td></tr>
</table>

[28] See https://tosotusa.com/product/liberty-series/.

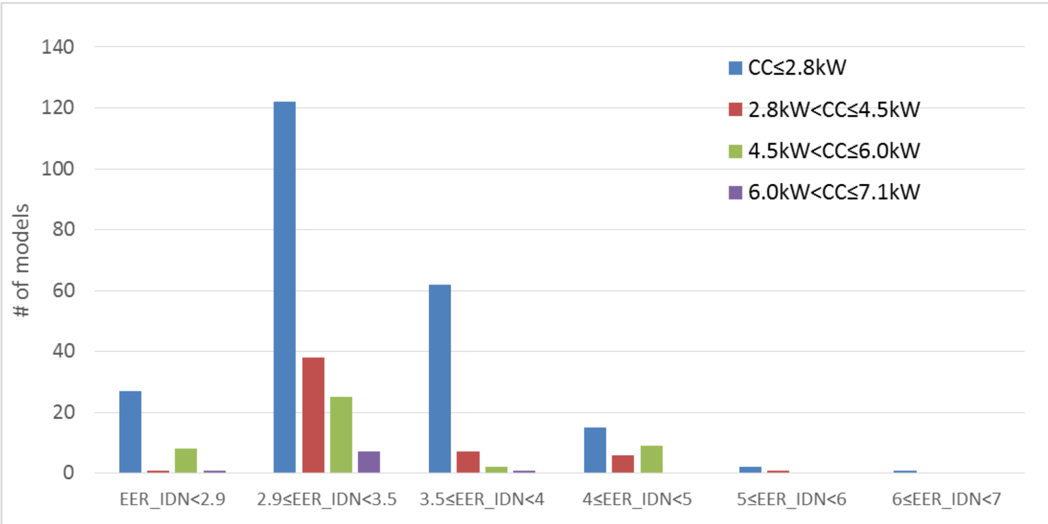
4.7. Other countries

According to recent articles in JARN, the share of ozone-depleting, high-GWP R-22 ACs in Southeast Asia, Latin America, the Middle East, and Africa is about 90% (JARN, 2017f). R-22 RACs dominant in these regions are mostly affordable, fixed-speed units. Because fixed-speed models cannot effectively react to changes in required cooling, their efficiency performance is limited.

The Association of Southeast Asian Nations (ASEAN) countries in the ASEAN Standards Harmonization Initiative for Energy Efficiency (SHINE) program—including Indonesia, Malaysia, Philippines, Singapore, Thailand, and Vietnam—have recently agreed to set a minimum EER (or a weighted EER[29]) of 2.9 (or a minimum CSPF of 3.08) by 2020 as a mandatory MEPS for all fixed- and variable-speed ACs below 3.52 kW in CC and to use a test method based on ISO 5151 and CSPF defined in ISO 16358 (ASEAN SHINE, 2017). The ASEAN SHINE program focuses on progressively phasing out inefficient ACs and increasing the share of high-efficiency ACs through harmonizing test methods and energy-efficiency standards, including adopting common MEPS requirements, and influencing consumer purchasing decisions (ASEAN SHINE, 2017; Shah et al., 2017). However, although market penetration of energy-efficient variable-speed inverter ACs is still low in the region, the ASEAN SHINE MEPS requirements are not stringent enough to reflect the market and technology trends.

According to a data set of RACs available in Indonesia, which was collected from the LBNL IDEA, the average efficiency of 335 models found on today's market is 3.3. About 89% of the 335 models have efficiencies equal to or greater than EER_{IDN} 2.9, the ASEAN SHINE requirement. The highest-efficiency RAC has EER 5.7 and EER_{IDN} 6.16 (Figure 19).[30] Letschert et al. (2017) analyzed the LBNL IDEA data and show that the current and planned regulations for RACs in Indonesia will have little or no impact, given that most of the market is already above the most stringent four-star level. Letschert et al. (2017) recommend a revision of the AC roadmap in order to move the market towards more efficient ACs.

[29] For example, Indonesian S&L define EER as a weighted average of EER at full load (35ºC) and EER at half load (35ºC). For fixed-speed ACs, Indonesian EER (EER_{IDN}) is equivalent to the traditional EER we use throughout the study.
[30] Here we use both the traditional EER and Indonesian EER (EER_{IDN}) for RACs in Indonesia.



- Total 335 split AC models in 2017
- Number of brands: 17
- Product-weighted average EER_{IDN}: 3.4
- Product-weighted average CC: 2.7 kW

Source: LBNL IDEA

Figure 19. Distribution of RAC models in Indonesia in 2017, by efficiency and CC

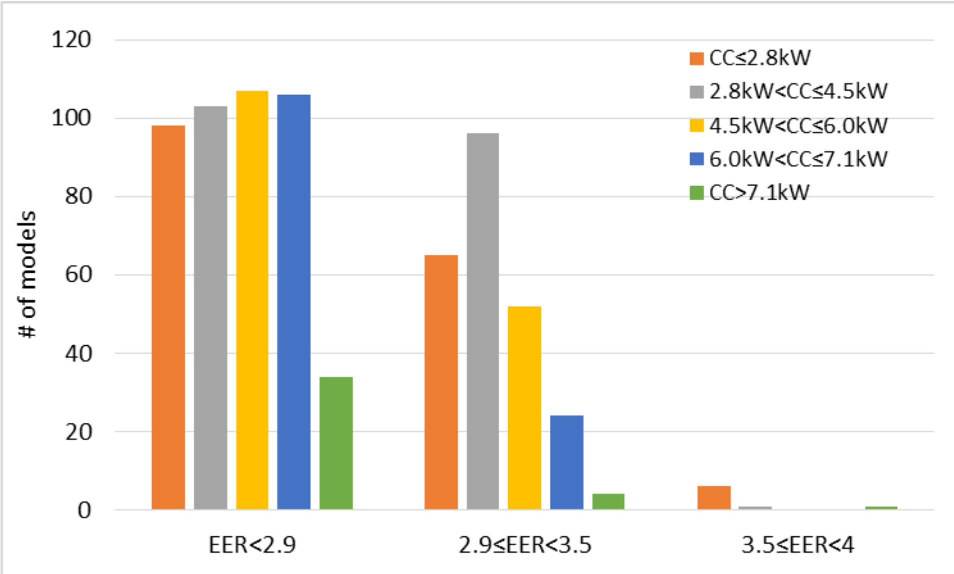
While R-22 fixed-speed RACs are still dominant in the country, energy-efficient variable-speed (i.e., inverter-driven) RACs and RACs with non-ozone-depleting, low-GWP refrigerants such as R-32 are commercially available. Table 16 shows the highest-efficiency RACs in Indonesia. All the listed models use R-32, except one small size (1.4 kW CC) RAC using R-410A.

Table 16. Highest-efficiency RACs in Indonesia (CC 0.75–2 RT)

RT	Manufacturer	Model Name	Heat pump?	CC (kW)	Efficiency[a]	Refrigerant	Price (USD)[b]
0.4	Electrolux	ESM 05CRI-A1E	No	1.4	EER_{IDN} 4.69	R-410	347
0.75	Daikin	FTXZ25NVM4	Yes	2.5	EER_{IDN} 6.16	R-32	1,510
1.0	Daikin	FTXZ35NVM4	Yes	3.5	EER_{IDN} 5.68	R-32	1,643
1.0	Panasonic	CS/CU-VU13SKP	No	3.4	EER_{IDN} 4.50	R-32	771
1.5	Daikin	FTXZ50NVM4	Yes	5.2	EER_{IDN} 5.11	R-32	1,776
2.0	Daikin	FTKV60NVM4	No	6.0	EER_{IDN} 4.77	R-32	1,184

[a] Note that Indonesian S&L defines EER as a weighted average of EER at full load (35°C) and EER at half load (35°C), i.e., Indonesia's EER (seasonal efficiency) = 0.4 × EER (100% load at 35°C) + 0.6 × EER (50% load at 35°C).
[b] 10000 Indonesian Rupiah = 0.75 US Dollar
Source: LBNL IDEA and web searches

In the Philippines, about 35% (697 models) of total RACs (including split and window units, certified to the S&L in 2016) were split-type AC models (GOVPH, 2016). The average EER of the 697 models is 2.9, and 36% of these models have efficiencies greater than EER 2.9, the ASEAN SHINE requirement. The highest-efficiency AC has EER 3.8 (Figure 20).



- Total 697 split AC models
- Product-weighted average EER: 2.9
- Product-weighted average CC: 4.5 kW

Source: GOVPH (2016)

Figure 20. Distribution of split AC models in the Philippines in 2016, by efficiency and CC

Driven by increasing incomes, electrification, and urbanization, demand for RACs in emerging economies with hot climates is expected to greatly increase energy consumption. For example, the RAC demand in the Middle East region, where climates are extremely hot, has been increasing.[31] The share of split ACs in the Middle East has been increasing, from 3.6 million units in 2011 to 4.6 million in 2016, surpassing window units (JARN, 2017h; JRAIA, 2017). Although fixed-speed split RACs with large CCs (7.0 kW and higher) are popular in the Middle East, a transition to R-410A is being carried out in the region—led by Saudi Arabia and the United Arab Emirates—and energy-efficient, variable-speed RACs using R-32 are commercially available in those economies (JARN, 2017h).

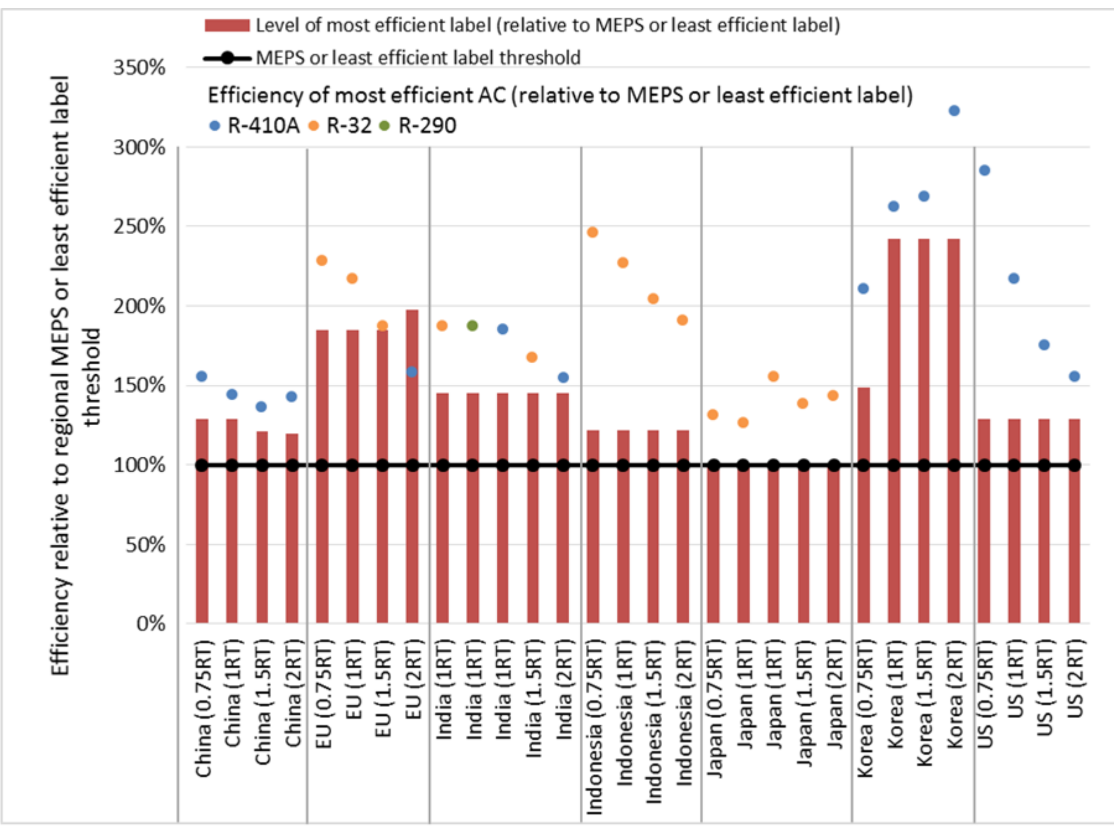
[31] According to Hillbrand (2016), based on the Integrated Surface Database data, the top 10 countries with 10 or more days of 47°C+ every year include Iraq, Iran, Kuwait, Algeria, Pakistan, Saudi Arabia, Qatar, India, United Arab Emirates, and the United States.

5. Discussion: development of energy-efficient RACs with low-GWP refrigerants

This section summarizes the findings from Section 4 and discusses issues associated with the development of energy-efficient RACs with low-GWP refrigerants. We also discuss the implications of our findings and provide recommendations for future research.

5.1. Opportunities for efficiency improvement in RACs

The energy-efficient models identified in China, Europe, India, Indonesia, Japan, South Korea, and the United States are produced by various global manufacturers. In South Korea and the United States, the most efficient RAC (i.e., ductless split) models use non-ozone-depleting but high-GWP R-410A refrigerant. In Europe, Japan, and Indonesia, the most efficient RAC models use low-GWP R-32 refrigerant. In China, the most efficient RAC models use R-410A or low-GWP R-32 refrigerants. In India, the most efficient RAC models use low-GWP R-32 or R-290 refrigerants, varying by manufacturer. Figure 21 shows that the most efficient models are significantly more efficient (in regional efficiency metric terms) than the most efficient level recognized by energy S&L programs in the economies where the models are available.



For example, the blue dot and red bar at "US (0.75RT)" should read that the efficiencies of the most efficient U.S. RAC (11.7 W/W) and the most efficient label (ENERGY STAR) requirement (5.27 W/W) are 2.85 times (285%) and 1.29 times (129%) as high as the U.S. MEPS (4.1 W/W). See Table B1 in Appendix B for information on AC models analyzed.

Figure 21. Efficiency of most-efficient models relative to MEPS or least-efficient labels

The highest-efficiency RACs are typically available in small sizes, particularly with 0.75-RT (2.5–2.6 kW CC) products.[32] This partly results from a commonly used design strategy of major AC manufacturers to optimize compressor efficiency when a unit is operated at variable frequency, which reduces production costs across a family of models by exploiting the fact that direct-current inverter-driven rotary compressors can operate at a wide range of frequencies, e.g., from 8 to 120 Hertz with a peak efficiency of 30 Hertz (Shah et al., 2013).[33] This results in higher efficiency at a lower frequency. In India and South Korea, larger-capacity units (1.5 RT or 2 RT) are more popular than are smaller-capacity units.

5.2. RACs with low-GWP alternative refrigerants

Until 2012, most AC manufacturers making a transition from R-22 chose R-410A. This non-ozone-depleting but high-GWP refrigerant is commonly used in mature RAC markets, except in Japan, where R-32 has already been adopted.[34] Although many developed countries have already transitioned to HFC refrigerants (e.g., R-410A, R-134a), higher-GWP and ozone-depleting refrigerants such as R-22 are still common in developing countries. A large fraction of the production in China geared toward satisfying demand in non- A5 Parties uses R-410A as refrigerant. (UNEP, 2014)

After Daikin launched the first R-32 RAC models (Urusara 7 series) in Japan in 2012, all Japanese manufacturers adopted R-32 for their AC products up to 16 kW in capacity in the domestic market (JARN, 2016a). To accelerate the adoption of R-32 globally, Daikin offered other companies worldwide free access to its own 93 patents, concerning production and sale of ACs using R-32 as a single-component refrigerant (Daikin, 2015). Chinese manufacturers and Thai local manufacturers have launched production of R-32 RACs (JARN, 2016a). R-32 RACs are estimated to be available in more than 50 countries, including Thailand, Indonesia, India, Vietnam, Australia, Italy, and Taiwan (JARN, 2016a). The total cumulative sales of R-32 ACs in the global market, including Japan, are estimated at more than 27 million units,[35] of which 10 million units were produced by Daikin only (JARN, 2017a, 2016a). At least another 4–5 million units are estimated to be sold in countries other than Japan.

Deutsche Gesellschaftfur Internationale Zusammenarbeit (GIZ) has implemented R-290 RAC production in China and India, with more projects underway worldwide. However, R-290 has not yet fully satisfied national safety standards in most countries except for models with small cooling

[32] Except in India, where the most efficient model is a 1-RT model, and in South Korea, where the most efficient model is a 2-RT model.
[33] This fact allows manufacturers to oversize a ductless AC system so it can supply more capacity than required at peak temperatures (Walczyk and Larson, 2016).
[34] In Japan, R-22 dominated the AC market (for commercial use) until 2001, then transitioned to R-407C and R-410A from 2002 onwards (Air Conditioner Evaluation Standards Subcommittee of Japan, 2006). From 2012, manufacturers in Japan, anticipating a transition to lower GWP refrigerants, began a second transition from R-410A to R-32.
[35] The data include split, window, and packaged ACs.

capacity (and therefore small charge). Since Godrej launched the first R-290 RAC models in India in 2012, the total cumulative sales of R-290 RACs in India reached 100,000 units in 2014 and 120,000 units in 2016 (JARN, 2017i; Kumar, 2014; Rajadhyaksha et al., 2015). Top Chinese manufacturers, Gree, Midea, and Haier already completed retrofits of production lines for R-290 RACs, and 40 R-290 AC models are registered in the S&L program in China.

To adopt a new AC refrigerant, manufacturers must balance thermodynamic performance (e.g., capacity, temperature, and efficiency), safety conditions (e.g., pressure, toxicity, and flammability), compatibility with system materials, availability, cost, and environmental impact (Goetzler et al., 2016). The optimal refrigerant for a heat-pumping or air-conditioning application may not be the same as a refrigerant used for very-low-temperature refrigeration (OTS, 2016). R-32 is an HFC refrigerant used most often in blends with other refrigerants. The widely-used R-410A is composed of non-flammable mixtures of refrigerants that include R-32. R-32 has a lower GWP, similar operating pressure, and lower compressor discharge compared with R-410A, but its GWP is higher than that of R-290, and it is mildly flammable, which might require design considerations to ensure the safety of technicians and building occupants. R-290 is classified as a flammable A3 refrigerant. Refrigerants are assessed to be safe if they meet international safety standards. The International Electrotechnical Commission (IEC) Standards for A2L and A3 refrigerants are currently under revision, and new standards are expected to be available in the next few years. Laboratory tests indicate that low-GWP refrigerants, including R-32 and R-290, have comparable or better efficiency performance compared with R-410A and R-22 (Abdelaziz and Shrestha, 2016; OTS, 2016; Abdelaziz et al., 2015).

Although this study is focused on two alternative low-GWP refrigerants—R-32 and R-290, which are already used in commercially available RACs—research and development efforts are still underway on potential alternative low-GWP AC refrigerants that have attractive performance and risk characteristics, including lower-flammability refrigerants (such as R-452B, which is a blend that contains R-125, R-1234yf, and R-32) and natural refrigerants (see Appendix C for characteristics of low-GWP alternatives for AC systems). See UNEP, 2016 for a more comprehensive summary of the new refrigerants being explored as low-GWP alternatives for R-410A. (UNEP, 2016)

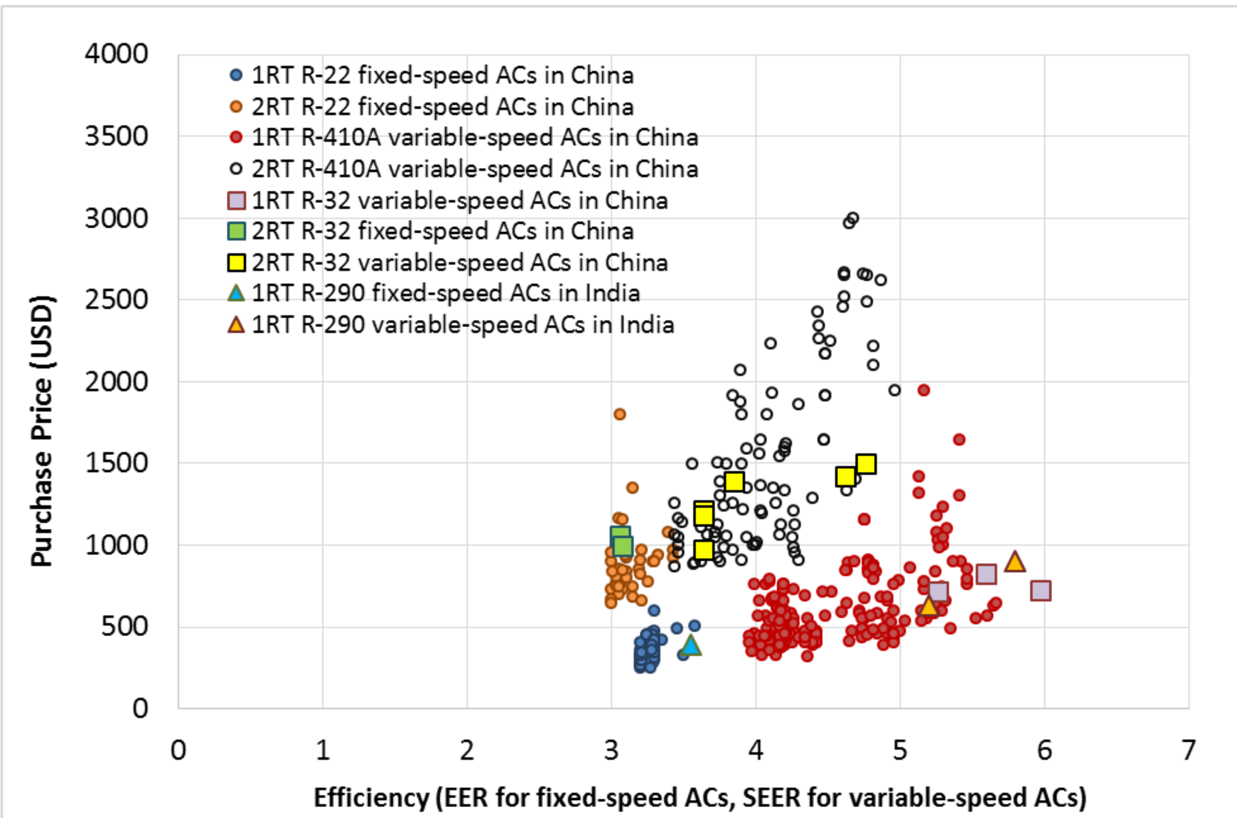
5.3. Affordable energy-efficient RACs with low-GWP alternative refrigerants

Outside of Japan, only a few RAC models are energy efficient and use low-GWP refrigerants. High efficiency is typically a feature of high-end products.[36] However, highly efficient, cost-

[36] Based on interviews with industrial experts and manufacturers.

competitive (less than USD 1,000 or 1,500 retail price, depending on size) RACs are also available.[37]

Figure 22 shows efficiency and price trends for 425 RAC models and 3 models in India, respectively, by product type, refrigerant, and CC. Higher-efficiency products tend to have a wider range of market price compared with lower-efficiency products, partly because high-efficiency models are often also sold as premium products bundled with other features. Thirty of 211 1-RT variable-speed units (R-410A and R-32) meet China SEER (or ISEER) 5 or higher with a price less than USD 1,000. Twenty of 98 2-RT variable-speed units (R-410A and R-32) meet China SEER 4 or higher with a price less than USD 1,500. Highly efficient, cost-competitive RACs with low-GWP refrigerants such as R-32 and R-290 are also commercially available in China, India, and Indonesia (Figure 22, Table 17).



Number of models: 74 (1-RT R-22 fixed-speed in China), 40 (2-RT R-22 fixed-speed in China), 208 (1-RT R-410A variable-speed in China), 92 (2-RT R-410A variable-speed in China), 3 (1-RT R-32 variable-speed in China), 2 (2-RT R-32 fixed-speed in China), 6 (2-RT R-32 variable-speed in China), 1 (1-RT R-290 fixed-speed in India), 2 (1-RT R-290 variable-speed in India)
Source: LBNL IDEA and web searches

Figure 22. Price vs. efficiency of 1-RT and 2-RT RACs

[37] Although we do not assess the cost-effectiveness of energy-efficient RACs in this study, here we roughly define cost-competitive energy-efficient RACs (which are mostly variable-speed inverter units) as those less than USD 1,000 (for 0.75- and 1.0-RT models) or USD 1,500 (for 1.5- and 2-RT models) in retail price.

Table 17. Examples of high-efficiency, cost-competitive RACs with low-GWP refrigerants (CC ≤ 7.2 kW)

Region	Brand	Model Name	CC (kW)	Seasonal Efficiency	Purchase price (USD)	Refrig-erant
China	Midea	KFR-26GW/BP3DN8Y-YA101(B1)	2.6	China APF 5.2	660	R-32
		KFR-35GW/BP3DN8Y-YA101(B1)	3.5	China APF 5.1	729	R-32
India	Daikin	JTKM35SRV16	3.5	ISEER 5.8	710	R-32
		JTKM50SRV16	5.0	ISEER 5.2	810	R-32
	Godrej	GSC 12 FIXH 7 GGPG	3.5	ISEER 5.8	825	R-290
		GSC 12 GIG 5 DGOG	3.5	ISEER 5.2	700	R-290
		GSC 18 GIG 5 DGOG	5.0	ISEER 4.9	840	R-290
Indonesia	Daikin	FTKC25PVM4	2.5	EER_{IDN} 4.14	361	R-32
		FTKC35PVM4	3.5	EER_{IDN} 4.14	472	R-32
		FTKC50NVM4	5.2	EER_{IDN} 4.95	644	R-32

Source: LBNL IDEA and web searches

5.4. Translation of regional energy efficiency metrics for RACs

The RAC market is largely global, yet variations in regional climates and the recent adoption of seasonal energy efficiency metrics (with unique temperature bins suited to each country's climate) make global comparison of RAC efficiencies difficult. In addition, it is difficult to identify similar variable-speed inverter RAC units available across a region, although exceptions exist.[38] As a result, policymakers around the world lack comparative data that might help them create more effective RAC efficiency targets as well as associated incentives and regulations.

The seasonal efficiency metrics used in China, India, Japan, and South Korea are highly consistent with ISO 16358 defined metrics (i.e., CSPF, HSPF, and APF), except they use region-specific climatic conditions and some adjustments. SEERs used in the United States and Europe[39] require more data points in outside temperature and part-load conditions than those used in the Asian countries or the ISO 16358 standard. All six major economies included in this study base their test procedures for ACs on adaptations of the ISO 5151 standard (Econoler et al., 2011). The ASEAN countries—including Indonesia, Malaysia, Philippines, Singapore, Thailand, and Vietnam—have agreed to use a test method based on ISO 5151: 2010 and CSPF defined in ISO 16358-1: 2013 (ASEAN SHINE, 2017). Therefore, the difference in seasonal efficiency metrics is primarily due to the outside temperature profiles used to aggregate steady-state and cyclic ratings into a seasonal

[38] For example, Daikin's Urusara 7 series (the first AC models running on R-32, launched in Japan in 2012) is available in Singapore, Indonesia, Malaysia, and the Philippines (as well as in Australia and Europe). The technical specifications of the Daikin Urusara 7 series are nearly identical across regions except for minor regional optimizations; however, their retail prices vary by region. For example, 0.75-RT models range from USD 1,400 to 2,200.

[39] EU SEER uses the regional climatic conditions and includes the impact of standby and other low-power modes.

efficiency value, as well as the ways of evaluating (measuring or calculating) performance at part-load operation into the metric.

Econoler et al. (2011) establish linear regression equations for converting efficiency metrics between China, the EU, Japan, South Korea, and the United States, to compare MEPS to each other. However, they stopped short of comparing the performance of commercially available ACs in different regional metrics. Phadke et al. (2017b) also establish similar relationships and estimate the performance of RACs, including highest-efficiency models, in efficiency metrics used in the six economies (China, the EU, India, Japan, South Korea, and the United States). The results of interregional AC efficiency conversion indicates that manufacturers design their high-efficiency products specifically to best perform under the local test procedure. If a high-efficiency model was designed to perform well under one regional test procedure, it could be possibly underperformed under another country's test procedure, leading to necessity for further performance optimization to be used in the country, and also suggest the potential to further improve AC efficiency in some regions where S&L programs, including test procedures for evaluating seasonal energy efficiency have not been improved or updated yet. See Appendix D and Phadke et al. (2017b) for details.

5.5. Further work

Shah et al. (2017) provide an overview of the current technical and policy contexts from which RAC-improvement opportunities could be identified and risks mitigated. Here, we identify the highest-efficiency levels of existing RACs in various markets to provide support for improving RAC efficiency policies. The performance of highest-efficiency commercially available RACs must be tested further to verify these data and to estimate the potential to improve cost and increase efficiency with low-GWP refrigerants.

Previous studies, such as those for the United States, analyzed actual appliance prices (refrigerators, ACs, and clothes washers) since energy-efficiency standards took effect and concluded that real prices were falling over time despite increases in efficiency (Dale et al., 2002, 2009). Van Buskirk et al. (2013) performed a retrospective investigation of multi-decade trends in price and life-cycle cost for home appliances in periods with and without energy efficiency S&L polices, and they concluded that introducing and updating appliance standards is not associated with a long-term increase in purchase price; rather, quality-adjusted prices undergo a continued or accelerated long-term decline. Another study demonstrated that the implementation of regulatory policies in Australia, Europe, Japan, and the United States during the 1990s and early 2000s did not increase the price of regulated products such as refrigerators/freezers, ACs, and clothes washers and dryers (Ellis et al., 2007). These price decreases are potentially explained by several factors including strategic pricing decisions by manufacturers, economies of scale and learning rates, design innovations, and resource substitution (Phadke et al., 2017a). The price of efficient products (which are currently sold as premium products) drops when they become the baseline products with the increasing stringency of standards (Spurlock, 2013). Prices in many markets (e.g., Japan, South Korea, and India) have continued to fall over time even with increases in efficiency (Phadke et al., 2017b; Abhyankar et al., 2017). It is helpful for policymakers to consider these long-term trends in price and efficiency.

In light of this evidence, engineering analysis is one approach typically used to estimate an appliance's potential for reduced energy consumption and associated incremental cost of efficiency improvements. Engineering analysis is a bottom-up, static approach that has been employed in the U.S. and EU efficiency standards rulemaking processes as well as by the BEE in India (Shah et al., 2016). This method typically provides a conservative (high-end) estimate of the increase in retail price that might occur if efficiency were improved. To make the estimate even more conservative, it can be based on an estimate of the markup for baseline models, which includes typical wholesale and retail costs. This approach could form the basis for conservative estimates of cost-benefit calculations related to individual consumers, manufacturers, and countries or regions to account for the additional costs, if any, compared to manufacturing conventional products.

To better develop cost-efficiency relationships for RACs, including those using low-GWP refrigerants, testing and design simulation could be conducted for vapor-compression-based AC systems to evaluate and estimate product performance, manufacturability, or reliability.

For all refrigerants, including R-22 and R-410A, RAC efficiency degrades with increased ambient temperature. However, research indicates that low-GWP refrigerants could have comparable or better performance than conventional refrigerants (R-22 or R-410A) in high-ambient-temperature environments (Abdelaziz et al., 2015). Given that energy-savings potential from ACs coupled with low-GWP refrigerants could vary by regional characteristics such as local climatic conditions and projected AC demand, there could be opportunities to achieve larger energy savings by adopting regional seasonal energy efficiency metrics in various countries including those with hot-climates. Further, standard temperature profiles defined in country- or region-specific standards might not represent some climate zones within the countries and could be modified to be more representative.

Given the technology available with leading global manufacturers, there appears to be a significant opportunity[40] to improve AC efficiency and reduce GHG emissions by deploying low-GWP, high-efficiency inverter products with more stringent requirements for market transformation programs for high efficiency and low-GWP RACs such as standards, labeling, procurement, performance assurance requirements for imports, or incentives.[41]

[40] While a full quantification of this opportunity requires more data in terms of baseline, sales, electricity prices, income and cost effectiveness, it is nevertheless very clear that the most efficient commercially available mini-split ACs are significantly more efficient than average mini-split ACs found in most markets around the world.

[41] Inverter ACs might not save as much in hot climates (in percentage terms) as they would in more moderate climates, because the number of hours of part-load operation would be lower.

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References

Abdelaziz, O., and S. Shrestha. 2016. *Soft-Optimized System Test of Alternative Lower GWP Refrigerants in 1.5-ton Mini-Split Air Conditioning Units*. TN 37831-6283. Oak Ridge, TN: Oak Ridge National Laboratory. http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP_Final_Reports/AHRI_Low_GWP_AREP_Rpt_062.pdf

Abdelaziz, O., S. Shrestha, J. Munk, R. Linkous, W. Goetzler, M. Guernsey, and T. Kassuga. 2015. *Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Mini-Split Air Conditioners*. ORNL/TM-2015-536. Oak Ridge, TN: Oak Ridge National Laboratory. https://energy.gov/sites/prod/files/2015/10/f27/bto_pub59157_101515.pdf

Abhyankar, N; Shah, N; Phadke, A; & Park, W. (2017). *Technical and Economic Aspects of Designing an Efficient Room Air-Conditioner Program in India*. LBNL 2001048. Berkeley, CA: Lawrence Berkeley National Laboratory http://escholarship.org/uc/item/7401k55r

Abhyankar, N., N. Shah, W. Park, and A. Phadke. 2017. *Accelerating Energy Efficiency Improvements in Room Air Conditioners in India: Potential, Costs-Benefits, and Policies*. LBNL-10035798. Berkeley, CA: Lawrence Berkeley National Laboratory.

Air Conditioner Evaluation Standards Subcommittee of Japan. 2006. *Final Summary Report by Air Conditioner Evaluation Standard Subcommittee, Energy Efficiency Standards Subcommittee of the Advisory Committee for Natural Resources and Energy*. https://www.eccj.or.jp/top_runner/pdf/tr_air_con_06.pdf

Andersen, S. O., M. L. Halberstadt and N. Borgford-Parnell. 2013. Stratospheric ozone, global warming, and the principle of unintended consequences—An ongoing science and policy success story. *Journal of the Air & Waste Management Association* 63:6, 607-647, DOI: 10.1080/10962247.2013.791349

ASEAN SHINE (Association of Southeast Asian Nations Standards Harmonization Initiative for Energy Efficiency). 2017. *Harmonization of Energy Performance Standards for Air Conditioners - A Regional Policy Roadmap*. http://www.switch-asia.eu/fileadmin/user_upload/Project_Downloads/Batch_4/ASEAN_SHINE/ASEAN_SHINE_Regional_policy_roadmap_2017.pdf

Baillargeon, P., N. Michaud, L. Tossou, and P. Waide. 2011. *Cooling Benchmarking Study Part 1: Mapping Component Report.* Prepared by Econoler and Navigant for the Collaborative Labeling and Appliance Standards Programs.

Calm, J. 2008. "The Next Generation of Refrigerants - Historical Review, Considerations, and Outlook." *International Journal of Refrigeration* 31:1123–33. http://www.jamesmcalm.com/pubs/Calm%20JM,%202008.%20The%20Next%20Generation%20of%20Refrigerants%20-%20Historical%20Review,%20Considerations,%20and%20Outlook,%20IJR.pdf

Daikin. 2015. "Daikin Offers Worldwide Free Access to Patents for Equipment Using Next-Generation Refrigerant: Facilitating global conversion to HFC-32 for air-conditioning, cooling and heat pump equipment." Press Release, September 10, 2015. http://www.daikin.com/press/2015/150910/

Dale, L., C. Antinori, M. McNeil, and J.E. McMahon. 2002. *Retrospective Evaluation of Declining Price for Energy Efficient Appliances*. American Council for an Energy-Efficient Economy (ACEEE) Summer Study on Energy-Efficiency in Buildings.

Dale, L., C. Antinori, M. McNeil, J.E. McMahon, and K.S. Fujita. 2009. "Retrospective Evaluation of Appliance Price Trends." *Energy Policy* 37:597–605.

Econoler, Navigant, CEIS, and ACEEE. 2011. *Cooling Benchmarking Study Report*. http://www.clasponline.org/en/Resources/Resources/PublicationLibrary/2012/Cooling-Benchmarking-Study.aspx

Ellis, M., N. Jollands, L. Harrington, and A. Meier. 2007. *Do energy efficient appliances cost more?* European Council for an Energy Efficient Economy (ECEEE) Summer Study.

Fridley, D., N. Khanna, N. Zhou, and M. McNeil. 2016. *Impacts of China's 2010 to 2013 Mandatory Product Energy Efficiency Standards: A Retrospective and Prospective Look*. 2016 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings.

Gerke, B., M. McNeil, and T. Tu. 2017. "The International Database of Efficient Appliances (IDEA): A new tool to support appliance energy-efficiency deployment." *Applied Energy* 205: 453-464.

Goetzler, W., M. Guernsey, J. Young, J. Fuhrman, and O. Abdelaziz. 2016. *The Future of Air Conditioning for Buildings*. Prepared by Navigant Consulting, Inc. and Oak Ridge National Laboratory for the U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2016/07/f33/The%20Future%20of%20AC%20Report%20-%20Full%20Report_0.pdf

GOVPH (Government of the Philippines). 2016. List of Room Air Conditioners with Approved Energy Label. Accessed 2016. https://www.doe.gov.ph/?q=energy-labelling

Hillbrand, A. 2016. "An Example High Ambient Temperature (HAT) Definition for the Montreal Protocol." Natural Resources Defense Council (NRDC) presentation, Geneva, April 5, 2016.

JARN (*Japan Air Conditioning, Heating and Refrigeration News*). 2017a. "Daikin Global Sales of R32 ACs Reach Ten Million in Over 50 Countries." June 24, 2017.

JARN. 2017b. "China." An update of AC market in Europe. January 23, 2017.

JARN. 2017c. "Europe." An update of AC market in Europe. May 28, 2017.

JARN. 2017d. "Japan." An update of AC market in Japan. January 23, 2017.

JARN. 2017e. "N. America." An update of AC market in North America. January 23, 2017.

JARN. 2017f. "Southeast Asia." An update of AC market in Southeast Asia. January 23, 2017.

JARN. 2017g. "International Symposium on R290 Refrigerant for RACs Held in Ningbo." May 27, 2017.

JARN. 2017h. "Middle East." An update of AC market in Middle East. January 23, 2017.

JARN. 2017i. "India". An update of AC market in India. January 23, 2017.

JARN. 2016a. "The Latest Trends of the Global R32 AC Market." October 22, 2016.

JARN. 2016b. "Inverter AC Market Expanding Rapidly in Southeast Asia." August 24, 2016.

JARN. 2015. "When Will R290 RACs Be Available?" July 18, 2015.

JRAIA (Japan Refrigeration and Air Conditioning Industry Association). 2017. *World Air Conditioner Demand by Region*.

Kimura, O. 2010. "Japanese Top Runner Approach for Energy Efficiency Standards." Socio-Economic Research Center (SERC). The Central Research Institute of Electric Power Industry. SERC Discussion Paper: SERC09035. http://criepi.denken.or.jp/jp/serc/research_re/download/09035dp.pdf

KRAAC (Korea Refrigeration and Air-conditioning Assessment Center). 2017. Authors' interview with KRAAC researchers.

Kumar, R. 2014. "R290 RAC Sales Exceed 100,000 Units in India." *JARN*, December 10, 2014.

Laminat, P. D. 2017. Overview of Fluids for AC Applications. February. ASHRAE Journal. http://www.johnsoncontrols.com/-/media/jci/be/united-states/specialty-pages/files/be_article_ashrae_overviewfluidsacapplications.pdf?la=en

Letschert, V., B. Gerke, M. McNeil, T. Tu, B. Dean, E. Sartono, J. Rajasa, and C. Gallinat. 2017. "Baseline Evaluation and Policy Implications for Air Conditioners in Indonesia." Presented at the 2017 Energy Efficiency in Domestic Appliances and Lighting (EEDAL) conference.

Li, J., S. Zeng, H. Bo, and Z. Tan. 2016. *Market Analysis of China Energy Efficient Products (MACEEP)*. CLASP and Top10 China. http://clasp.ngo/en/Resources/Resources/PublicationLibrary/2013/Market-Analysis-China-Energy-Efficient-Products

Mathur, A., S. O. Andersen, S. Carvalho, M. Gonzalez, K. Mangotra, and R. Shende. 2017. Leap Frogging to Super Efficiency," IGSD: http://www.igsd.org/wp-content/uploads/2017/08/Updated-EESL-AC-Bulk-Procurement-4-Aug.pdf.

McLaughlin, C. 2017. "Is China moving to R290 for air-conditioning?". http://hydrocarbons21.com/articles/7584/is_china_moving_to_r290_for_air_conditioning

McNeil, M.A., N. Bojda, W. Park, M. Zhou, J. Ke, and J. Choi. 2012. *Business Case for Energy Efficiency in Support of Climate Change Mitigation, Economic and Societal Benefits in the Republic of Korea*. LBNL-6219E. Berkeley, CA: Lawrence Berkeley National Laboratory. https://ies.lbl.gov/publications/business-case-energy-efficiency-1

MIIT (Ministry of Industry and Information Technology of the People's Republic of China). 2016. List of 2016 Top Runner Program listed room air conditioners. Accessed 2016. http://www.miit.gov.cn/n1146295/n1652858/n1653100/n3767755/c4678082/content.html

OTS (Optimized Thermal Systems, Inc.). 2016. *An Evaluation of R32 for the US HVAC&R Market*. http://www.optimizedthermalsystems.com/images/pdf/about/An-Evaluation-of-R32-for-the-US-HVACR-Market.pdf

Phadke, A., W. Park, N. Abhyankar, and N. Shah. 2017a. "Relationship between Appliance Prices and Energy-Efficiency Standards and Labeling Policies: Empirical Evidence from Residential Air Conditioners." Presented at the 2017 Energy Efficiency in Domestic Appliances and Lighting (EEDAL) conference.

Phadke, A., W. Park, N. Shah, H. Kang, J. and Choi. 2017b. *Rating the performance of energy-efficient air conditioners in various regional metrics*. Draft report. Berkeley, CA: Lawrence Berkeley National Laboratory.

Rajadhyaksha, D., B.J. Wadia, A. Acharekar, and D. Colbourne. 2015. "The first 100 000 HC-290 split air conditioners in India." *International Journal of Refrigeration* 60:289–96. http://dx.doi.org/10.1016/j.ijrefrig.2015.07.032

Schleicher, T. 2013. "Topten Product Criteria Paper on Room Air Conditioners." http://www.topten.eu/uploads/File/deliverables_max/D3.2%20Update_Room_Air_Conditioners_Criteria_Paper_Update_final.pdf

Seidel, S., J. Ye, S.O. Andersen, and A. Hillbrand. 2016. *Not-In-Kind Alternatives to High Global Warming HFCs.* Center for Climate and Energy Solutions (C2ES). https://www.c2es.org/publications/not-kind-alternatives-high-global-warming-hfcs

Shah, N., P. Waide, and A. Phadke. 2013. *Cooling the Planet: Opportunities for Deployment of Superefficient Room Air Conditioners*. LBNL-6164E. Berkeley, CA: Lawrence Berkeley National Laboratory. https://ies.lbl.gov/publications/cooling-planet-opportunities

Shah, N., M. Wei, V. E. Letschert, and A. Phadke. 2015. *Benefits of Leapfrogging to Superefficiency and Low Global Warming Potential Refrigerants in Room Air Conditioning*. LBNL-1003671. Berkeley, CA: Lawrence Berkeley National Laboratory. https://ies.lbl.gov/publications/benefits-leapfrogging-superefficiency

Shah, N., N. Khanna, N. Karali, W. Park, Y. Qu, and N. Zhou. 2017. *Opportunities and Risks for Simultaneous Efficiency Improvement and Refrigerant Transition in Air Conditioning*. Berkeley, CA: Lawrence Berkeley National Laboratory.

Shah, N., N. Abhyankar, W. Park, A. Phadke, S. Diddi, D. Ahuja, P.K. Mukherjee, and A. Walia. 2016. *Cost-Benefit of Improving the Efficiency of Room Air Conditioners (Inverter and Fixed Speed) in India*. LBNL-1005787. Berkeley, CA: Lawrence Berkeley National Laboratory.

Spurlock, C.A. 2013. *Appliance Efficiency Standards and Price Discrimination*. LBNL-6283. Berkeley, CA: Lawrence Berkeley National Laboratory.

Topten EU. 2012. "Room air conditioners: Recommendations for policy design." http://www.topten.eu/uploads/File/Room%20air%20conditioners%20Recommendations_May%202012.pdf

UNEP, 2014 Assessment report of the Technology and Economic Assessment Panel, UNEP Nairobi, Ozone Secretariat, April 2014

UNEP, 2016 "Report of the Technology and Economic Assessment Panel, volume 1 Decision XXVII/4 Task Force Update Report: Further Information on Alternatives to Ozone Depleting Substances", UNEP Nairobi, Ozone Secretariat, September 2016.

US DOE (United States Department of Energy). 2015a. *Technical Support Document: Energy Efficiency Program For Consumer Products: Residential Central Air Conditioners and Heat Pumps*. Washington, DC: US DOE.

US DOE. 2015b. "Explaining Central Air Conditioner & Heat Pump Standards." https://www.energy.gov/sites/prod/files/2015/11/f27/CAC%20Brochure.pdf

US DOE. 2011. *Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Residential Clothes Dryers and Room Air Conditioners*. Washington, DC: US DOE.

Van Buskirk, R.D., C.L.S. Kantner, B.F. Gerke, and S. Chu. 2013. "A retrospective investigation of energy efficiency standards: policies may have accelerated long term declines in appliance costs." *Environmental Research Letters* 9:114010. http://iopscience.iop.org/article/10.1088/1748-9326/9/11/114010/meta;jsessionid=775D445E29EA9F89ED4536AC2CEA4298.c4.iopscience.cld.iop.org

Velders, G. J. M. D. W. Fahey, J. S. Daniel, M. McFarland, and S. O. Andersen (2009). The large contribution of projected HFC emissions to future climate forcing, Proceedings of the National Academy of Sciences (PNAS). 106:10949–10954.

Walczyk, J., and A. Larson. 2016. *Ductless Mini-Split Heat Pump Systems: The Answers to Questions about Efficiency You Didn't Know You Had*. 2016 American Council for an Energy Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings.

Zaelke, D., N. Borgford-Parnell, and S. O. Andersen. 2017. Primer on HFCs: Fast action under the Montreal Protocol can limit growth of hydrofluorocarbons (HFCs), prevent 100 to 200 billion tonnes of CO2-eq by 2050, and avoid up to 0.5°C of warming by 2100. http://www.igsd.org/wp-content/uploads/2017/05/HFC-Primer-19May2017.pdf

Appendix A. Energy Efficiency Standards and Labels

Table A1. China's energy-efficiency label thresholds for fixed-speed RACs

Type	Cooling Capacity (CC)	Grade 1	Grade 2	Grade 3
Split	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

Source: Chinese Efficiency Standard GB 12021.3-2010 ("The minimum allowable value of the energy efficiency and energy efficiency grades for RACs")

Table A2. China's energy-efficiency label thresholds for variable-speed RACs

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

Source: Chinese Efficiency Standard GB 21455-2013 ("Minimum allowable values of the energy efficiency and energy efficiency grades for variable-speed RACs")

Table A3. The EU's energy-efficiency classes and Eco-design requirements for RACs

Labels		
	SEER (Cooling)	SCOP (Heating)
A+++	SEER ≥ 8.50	SCOP ≥ 5.10
A++	6.10 ≤ SEER < 8.50	4.60 ≤ SCOP < 5.10
A+	5.60 ≤ SEER < 6.10	4.00 ≤ SCOP < 4.60
A	5.10 ≤ SEER < 5.60	3.40 ≤ SCOP < 4.00
B	4.60 ≤ SEER < 5.10	3.10 ≤ SCOP < 3.40
C	4.10 ≤ SEER < 4.60	2.80 ≤ SCOP < 3.10
D	3.60 ≤ SEER < 4.10	2.50 ≤ SCOP < 2.80
E	3.10 ≤ SEER < 3.60	2.20 ≤ SCOP < 2.50
F	2.60 ≤ SEER < 3.10	1.90 ≤ SCOP < 2.20
G	SEER < 2.60	SCOP < 1.90

Eco-design		
	SEER	SCOP
GWP > 150 for < 6 kW	4.60	3.80
GWP < 150 for < 6 kW	4.14	3.42
GWP > 150 for 6-12 kW	4.30	3.80
GWP < 150 for 6-12 kW	3.87	3.42

Source: Topten EU (2013)
http://www.topten.eu/uploads/File/deliverables_max/D3.2%20Update_Room_Air_Conditionners_Criteria_Paper_Update_final.pdf

Table A4. Star ratings for RACs in India

<table>
<tr><th colspan="2">Voluntary (June 29, 2015 – Dec 31, 2017)
Mandatory (Jan 1, 2018 – Dec 31, 2019)</th></tr>
<tr><td>1-Star</td><td>3.10 ≤ ISEER ≤ 3.29</td></tr>
<tr><td>2-Star</td><td>3.30 ≤ ISEER ≤ 3.49</td></tr>
<tr><td>3-Star</td><td>3.50 ≤ ISEER ≤ 3.99</td></tr>
<tr><td>4-Star</td><td>4.00 ≤ ISEER ≤ 4.49</td></tr>
<tr><td>5-Star</td><td>4.50 ≤ ISEER</td></tr>
</table>

Source: Bureau of Energy Efficiency (Schedule-19 Variable Capacity Air Conditioners, 29th June 2015)
https://www.beestarlabel.com/Content/Files/Inverter%20AC%20schedule%20final.pdf

Table A5. Japan Top Runner program's target standards in APF for RACs

<table>
<tr><th></th><th>CC
< 3.2 kW</th><th>3.2 < CC
≤ 4.0 kW</th><th>4.0 < CC
≤ 5.0 kW</th><th>5.0 < CC
≤ 6.3 kW</th><th>6.3 < CC
≤ 7.1 kW</th><th>7.1 < CC
≤ 28.0 kW</th></tr>
<tr><td>Non-ducted/wall-mounted</td><td>5.8/6.6[a]</td><td>4.9/6.0[a]</td><td>5.4</td><td>4.9</td><td>4.4</td><td>-</td></tr>
<tr><td>Split type other than non-ducted/wall-mounted</td><td>5.0</td><td>4.7</td><td colspan="3">4.2</td><td>-</td></tr>
<tr><td>Multi-type</td><td colspan="2">5.1</td><td colspan="3">5.3</td><td>5.4</td></tr>
</table>

[a] Target APF for dimension-defined type/target APF for free–dimension type
Source: Final Report by Air Conditioner Evaluation Standard Subcommittee, Energy Efficiency Standards Subcommittee of the Advisory Committee for Natural Resources and Energy (2008, 2006)

Table A6. South Korea's energy-efficiency standards and labels for split ACs (cooling only)

	Energy Frontier	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
CC < 4 kW	6.54 ≤ R	5.00 ≤ R	4.59 ≤ R < 5.00	4.19 ≤ R < 4.59	3.78 ≤ R < 4.19	3.37 ≤ R < 3.78
4 ≤ CC < 10 kW	9.36 ≤ R	7.20 ≤ R	6.14 ≤ R < 7.20	4.40 ≤ R < 6.14	3.50 ≤ R < 4.40	2.97 ≤ R < 3.50
10 ≤ CC < 17.5 kW	7.54 ≤ R	5.80 ≤ R	5.04 ≤ R < 5.80	4.28 ≤ R < 5.04	3.52 ≤ R < 4.28	2.76 ≤ R < 3.52
17.5 ≤ CC < 23 kW	6.17 ≤ R	4.11 ≤ R	3.69 ≤ R < 4.11	3.30 ≤ R < 3.69	2.95 ≤ R < 3.30	2.63 ≤ R < 2.95

The AC efficiency metric, R, is equivalent to CSPF for cooling-only units. Since 2015, multi-split ACs have been included in the 4kW ≤ CC < 10kW product category. Since 2015, "smart" features are required for a product to qualify for Level 1 and Energy Frontier in the 4 kW ≤ CC < 10kW product category.
Source: Korea's Regulation on Energy Efficiency Labeling & Standards - Notice No. 2016-137 of Ministry of Trade, Industry and Energy (MOTIE)

Table A7. U.S. energy-efficiency standards for split ACs

	North	Southeast	Southwest
SEER	13	14	14
EER	-	-	12.2 (< 45,000 Btu/h) 11.7 (≥ 45,000 Btu/h)

Unit: Btu/(h·W)

In the United States, EER is defined as a ratio of the CC in Btu/h to the power input value in watts at any given set of rating conditions expressed in Btu/(W· h), and SEER is defined as the total heat removed from the conditioned space during the annual cooling season, expressed in Btus, divided by the total electrical energy consumed by the AC or heat pump during the same season, expressed in watt-hours. 1 Btu/h is equivalent to 0.293 W.

Source: US DOE (2015b)

Table A8. U.S. energy-efficiency standards for other central ACs and heat pumps

Product Class	SEER	HSPF
Split-system Heat Pumps	14	8.2
Split-package ACs	14	-
Split-package Heat Pumps	14	8.0
Small-duct, High-velocity Systems	12	7.2
Space-constrained ACs	12	-
Space-constrained Heat Pumps	12	7.4

Unit: Btu/(h·W)

Source: US DOE (2015b)

Table A9. U.S. ENERGY STAR criteria for residential air source heat pumps and central ACs

	Product Class	SEER	EER	HSPF
Tier 1	Split Systems	≥ 14	≥ 11.5	≥ 8.2
	Single Package Equipment	≥ 14	≥ 11	≥ 8.0
Tier 2	Split Systems	≥ 14.5	≥ 12	≥ 8.2
	Single Package Equipment	≥ 14	≥ 11	≥ 8.0

Unit: Btu/h·W

Source: U.S. ENERGY STAR Program Requirements for Residential Air Source Heat Pump (ASHPs) and Central Air Conditioner Equipment (version 5).
https://www.energystar.gov/sites/default/files/ENERGY%20STAR%20CAC-ASHP%20V5.0.pdf

Appendix B. List of Highest-Efficiency RACs

Table B1. Highest-efficiency RACs identified in this study[a]

	RT[b]	Brand	Model Name	Cooling/ Heating	CC (kW)	Seasonal Efficiency[c]	Refrigerant
China1	0.75	Mitsubishi	MSZ-(P)ZHJ09VA	C/H	2.5	China APF 5.45	R-410A
China2	1.0	Midea	KFR-35GW/BP3DN8Y-YA101(B1)	C/H	3.5	China APF 5.05	R-32
China3	1.5	Midea	KFR-51LW/BP3DN8Y-YB200(B1)*	C/H	5.2	China APF 4.51	R-32
China4	2.0	Daikin	FVXF172NC-W*	C/H	7.2	China APF 4.43	R-410A
EU1	0.75	Panasonic	CS-VZ9SKE/CU-VZ9SKE	C/H	2.5	EU SEER 10.5	R-32
EU2	1.0	Panasonic	CS-VZ12SKE/CU-VZ12SKE	C/H	3.5	EU SEER 10.0	R-32
EU3	1.5	Daikin	FTXZ50N/RXZ50N	C/H	5.0	EU SEER 8.6	R-32
EU4	2.0	Mitsubishi	MSZ-GF71VE/MUZ-GF71VE	C/H	7.1	EU SEER 6.8	R-410A
India1	1.0	Daikin	JTKM35SRV16	C	3.6	ISEER 5.8	R-32
India2	1.0	Godrej	GSC 12 FIXH 7 GGPG[d]	C	3.5	ISEER 5.8	R-290
India3	1.0	Hitachi	RAU512AWEA	C	3.6	ISEER 5.75	R-410A
India4	1.5	Daikin	JTKM50SRV16	C	5.0	ISEER 5.2	R-32
India5	2.0	Mitsubishi	MSY-GK24VA	C	6.7	ISEER 4.8	R-410A
Indonesia1	0.75	Daikin	FTXZ25NVM4	C/H	2.5	EER_{IDN} 6.2	R-32
Indonesia2	1.0	Daikin	FTXZ35NVM4	C/H	3.5	EER_{IDN} 5.7	R-32
Indonesia3	1.5	Daikin	FTXZ50NVM4	C/H	5.0	EER_{IDN} 5.1	R-32
Indoensia4	1.7	Daikin	FTKV60NVM4	C/H	6.0	EER_{IDN} 4.8	R-32
Japan1	0.75	Hitachi	RAS-X25G	C/H	2.5	Japan APF 7.6	R-32
Japan2	1.0	Panasonic	CS-WX407C2	C/H	4.0	Japan APF 7.6	R-32
Japan3	1.0	Hitachi	RAS-X40G2[e]	C/H	4.0	Japan APF 7.6	R-32
Japan4	1.5	Mitsubishi	MSZ-FZ5617S	C/H	5.6	Japan APF 6.8	R-32
Japan5	2.0	Mitsubishi	MSZ-FZ7117S (FZV7117S)	C/H	7.1	Japan APF 6.3	R-32
Korea1[f]	0.75	Samsung	AR06HVAF1WK	C	2.3	Korea CSPF 7.1	R-410A
Korea2	1.0	LG	SNQ111BSF1W/SUQ111SAF	C	4.2	Korea CSPF 7.8	R-410A
Korea3	1.5	LG	SNQ131BMF1W/SUQ131MAF	C	5.2	Korea CSPF 8.0	R-410A
Korea4	2.0	Samsung	AF18J9975WWK*	C	7.2	Korea CSPF 9.6	R-410A
US1	0.75	Gree	SAP09HP230V1BO	C/H	2.6	US SEER 11.7	R-410A
US2	1.0	Gree	GWH12YD-D3DNA1A/O	C/H	3.5	US SEER 8.9	R-410A
US3	1.5	Gree	GWH18YD-D3DNA1A/O	C/H	5.3	US SEER 7.2	R-410A
US4	1.8	LG	LAN240HYV1/LAU240HYV1	C/H	6.4	US SEER 6.4	R-410A

* Floor-standing type (all other models are wall-mounted type)

a. Ductless split type, CC 0.75–2 RT

b. RT is a unit of power to describe the heat-extraction capacity of refrigeration and air conditioning equipment. 1 RT is approximately equivalent to 12,000 Btu/h or 3.5 kW.

c. The selected models show the highest efficiency using the regional efficiency metric.

d. On March 7, 2017, Godrej announced the launch of a new inverter AC with ISEER 5.8. The previous version is GSC 12 GIG 5 DGOG with ISEER 5.2.

e. This model is a "dimension-defined" type, which is an indoor device that is less than 800 mm in width and 295 mm in height. Others are categorized as "dimension-free." The target APF for dimension-defined types is less than the target for dimension-free types.

f. The most efficient models in South Korea are floor-standing types with CC ranging from 6.5 to 7.2 kW.

Appendix C. Low-GWP Alternatives for Stationary[42] Air Conditioning

Table C1. Examples of low-GWP alternatives for stationary ACs

Type	Chemical	Safety Class[a]	GWP[b]	Flammability[c]	Comments
HCFCs	HCFC-22	A1	1,760	1	
HFCs	HFC-410A	A1	1,900	1	
	HFC-134a	A1	1,300	1	
Low-GWP Alternatives					
HFCs	HFC-32	A2L	677	2L	Small self-contained AC systems available. Small split AC systems also available in parts of Asia, India, and Europe.
HFOs	HFO-1234yf HFO-1234ze	A2L A2L	< 1 < 1	2L 2L	Considered for ducted and rooftop units, subject to safety standards and codes.
	HFO-1336mzz(Z)	A1	2	1	U.S. EPA Significant New Alternative Policy (SNAP) approved in 2016 for use in industrial process AC (new equipment).
HFO/HFC Blends	R-446A R-447A R-452B R-454B	A2L A2L A2L A2L	460 570 680 470	2L 2L 2L	Newly developed blends being developed for small split ACs. Also for multi-splits, VRF systems, and ducted systems subject to safety standards and codes.
	R-450A R-513A R-513B	A1 A1 A1	550 570 540	1 1 1	Possible alternatives for ducted and packaged rooftop units.
HCs	HC-290 HC-1270	A3 A3	3 2	3 3	Limited availability for small split ACs in Europe and parts of Asia owing to flammability concerns.
Ammonia	R-717	B2L	0	1	Used only for chillers with small capacities owing to costs.
Water (H_2O)	R-718	A1	N/A	1	Limited to special applications for chillers.
CO_2	R-744	A1	1	1	Limited applicability for stationary AC systems and chillers based on reduced efficiency in high ambient temperatures. Market may not support development cost of components.

[a] ASHRAE 34 safety classification where A1 is lower toxicity/no flame propagation, A2/A2L is lower toxicity/low flammability, A3 is lower toxicity/higher flammability, B1 is higher toxicity/no flame propagation, B2/B2L is higher toxicity/low flammability, and B3 is higher toxicity/higher flammability.
[b] 100-year time horizon GWP relative to CO_2 (AR5).
[c] Refrigerant flammability classified based on ASHRAE 34 where 1 is no flame propagation, 2L is lower flammability, 2 is flammable, and 3 is higher flammability.Source: Larminat (2017), Seidel et al. (2016)

[42] Stationary AC systems are used for residential, commercial, and industrial cooling applications. Self-contained AC systems include sealed units used for cooling small rooms in residential and commercial buildings. Split AC systems include small split AC systems used to cool single rooms in residential and commercial buildings. Large AC systems include large and multi-split systems, variable refrigerant flow (VRF) systems, and ducted and packaged rooftop systems that cool air supplied to a room or to a whole building (Seidel et al., 2016).

Appendix D. Interregional Conversion of Seasonal Energy Efficiency Performance

As briefly discussed in Section 5.4, Phadke et al. (2017b) use regression results based on test data from 23 models ranging in cooling capacity from 3 kW to 14.5 kW and other regression results from Econoler et al. (2011) to establish relationships across various regional energy performance metrics with a focus on variable-speed RACs. Table D1 shows efficiencies of RACs in one region and estimated efficiencies in other regional metrics. For example, US SEER 9 is estimated to be equivalent to China APF 4.2–5.1, EU SEER 7.1-10.0, India SEER 4.5, Japan APF 8.4–8.5, and Korea CSPF 8.8–9.7 under each regional efficiency metric.

Table D1. Interregional conversion of seasonal energy efficiency for variable-speed (inverter-driven) split RACs in Watts/ Watt (W/W)

Regional Efficiency Performance (X)		Estimated Efficiency (converted from X)					
		China APF	EU SEER	India SEER	Japan APF	Korea CSPF	US SEER[43]
China APF	4	4.0	5.60-6.19	3.94–4.24	5.34–6.42	5.94–7.00	6.00–7.09
	5	5.0	6.56–7.34	4.08–5.17	6.00–8.00	6.59–8.58	7.87–8.96
	6	6.0	7.52–8.50	4.45–6.10	7.67–9.58	8.24–10.26	9.75–10.83
EU SEER	8	4.39-5.27	8.0	4.57	6.90–8.92	7.81–9.60	7.14-9.16
	9	4.64-5.78	9.0	4.79	7.69–10.28	8.75–11.03	8.06-10.33
	10	4.89–6.28	10.0	5.01	8.49–11.65	9.70–12.46	8.97-11.50
India SEER	4	3.79-4.18	5.94	4.0	6.13	6.67	6.66
	5	4.57-5.02	6.79	5.0	7.27	7.86	8.30
	6	5.35-5.86	7.65	6.0	8.41	9.04	9.94
Japan APF	6	3.87-4.20	5.92-6.86	4.10	6.0	6.55-6.73	6.09-6.64
	7	3.97-4.52	6.35-8.04	4.20	7.0	7.44-7.84	7.19-7.42
	8	4.08-4.84	6.78-9.23	4.29	8.0	8.32-8.95	8.18-8.29
Korea CSPF	8	4.04-4.71	6.65-8.19	4.26	7.04-7.43	8.0	7.29-7.86
	9	4.16-5.05	7.15-9.23	4.37	7.86-8.41	9.0	8.25-8.70
	10	4.28-5.40	7.65-10.28	4.48	8.69-9.40	10.0	9.20-9.54
US SEER	8	4.08-4.74	6.58-8.93	4.32	7.39-7.65	7.89-8.67	8.0
	9	4.24-5.13	7.05-10.01	4.50	8.37-8.52	8.84-9.69	9.0
	10	4.40-5.52	7.52-11.09	4.67	9.36-9.38	9.80-10.70	10.0

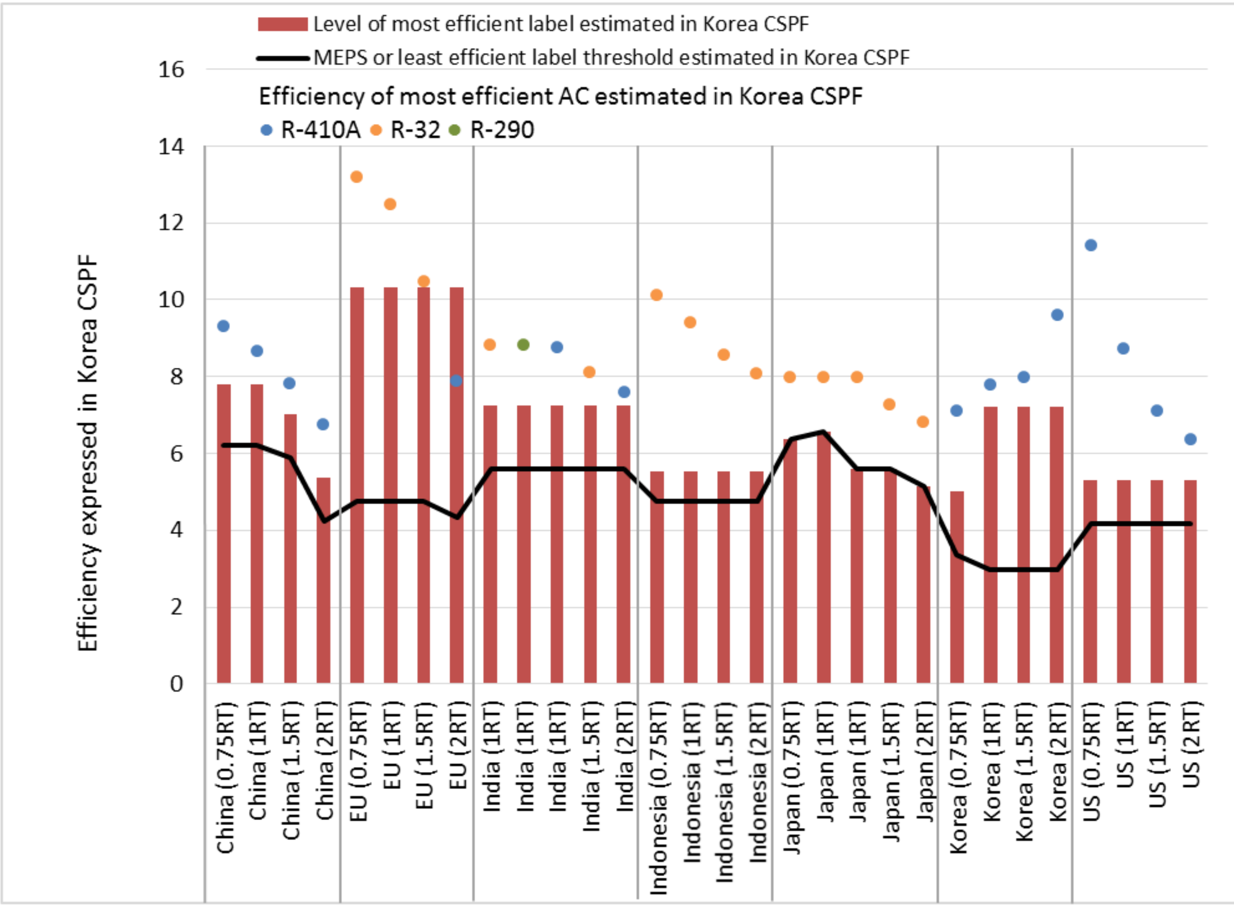
The selected ranges of regional efficiency performance include the efficiency levels of the highest-efficiency RACs identified in this analysis.

India SEER is based on only one condition of efficiency evaluation, while other efficiencies with ranges are based on multiple conditions or consider results from both Phadke et al. (2017b) and Econoler et al. (2011).

Source: Authors' work based on Phadke et al. (2017b) and Econoler et al. (2011)

[43] Note: US SEER is typically reported in BTU/hr/W. To convert from the values shown here to the typical values reported in the US market, multiply by 3.412.

The inter-regional efficiency conversion relationships provide indicative efficiency of ACs in one region under the efficiency metrics of other regions. Figure D1 shows the conversion results of Figure ES-1 (same as Figure 22).



We note that manufacturers design their high-efficiency products specifically to best perform under the local test procedure. If a high-efficiency model was designed to perform well under one regional test procedure, it could be possibly underperformed under another country's test procedure, leading to necessity for further performance optimization to be used in the country.

Figure D1. Indicative efficiency converted in Korea CSPF of most-efficient models relative to MEPS or least-efficient labels

The analytical method entails uncertainty when making interregional comparisons. If the individual models exhibit a large scatter about a mean scaling relation, then selecting only the highest performers in Market A is statistically guaranteed to yield converted values in Market B that are biased high relative to the values one would measure using Market B's test procedure (on average). A high-efficiency model in one market is designed to perform well under the regional test procedure. It might not perform as well, relative to other models, under some other country's test procedure. This effect can be mitigated to some degree by averaging the results of a certain set of models, rather than selecting one particular model on the market. Further analysis, including product testing, is needed to verify the performance of the apparently highest-performing models in various regions.