LBNL Report

Challenges and Recommended Policies for Simultaneous Global Implementation of Low-GWP Refrigerants and High Efficiency in Room Air Conditioners

Authors:

Won Young Park, Nihar Shah, Chao Ding, Yi Qu

Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory
International Energy Studies Group, China Energy Group

March 2019

This work was supported by the Institute for Governance and Sustainable Development under Lawrence Berkeley National Laboratory Contract No. DE-AC02-05CH11231.

Abstract

Increasing incomes, electrification, and urbanization—as well as a warming world—are driving up the global stock of air conditioners (ACs), particularly in emerging economies with hot climates. AC energy consumption is expected to increase substantially as the global stock of room ACs rises to 1.5 billion in 2030 and 2.5 billion in 2050. Hence, improving AC energy efficiency will be critical to reducing AC energy, cost (consumer lifecycle cost, electricity generation cost, etc.), peak load, and emissions impacts. The 2016 Kigali Amendment to the Montreal Protocol offers an opportunity to improve AC energy efficiency in tandem with the phasedown of high global warming potential (GWP) hydrofluorocarbon (HFC) refrigerants. Based on the most recent information, a literature review, and interviews with manufacturers and industry experts, we find the main barriers to deploying high-efficiency ACs include concerns about market demand and cost, which could be mitigated by appropriately improved design of market-transformation programs such as standards and labeling, incentive, and procurement programs. The main barriers to the low-GWP refrigerant transition include the need for timely revision of safety standards and associated costs for capacity-building activities allowing safe use of low-GWP refrigerants in ACs. Policy action and the market transformation can be accelerated by advancing the refrigerant transition and efficiency improvements in parallel.

ACRONYMS

AC	air conditioner
AHRI	Air-conditioning, Heating & Refrigeration Institute
ANSI	American National Standards Institute
APF	annual performance factor
AREP	alternative refrigerants evaluation program
ASEAN	Association of Southeast Asian Nations
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CARB	California Air Resources Board
CC	cooling capacity
COP	coefficient of performance
CSPF	cooling seasonal performance factor
EER	energy efficiency ratio
EER_{IDN}	Indonesian EER
EPA	U.S. Environmental Protection Agency
EU	European Union
EU SEER	European Union seasonal energy efficiency ratio
GWP	global warming potential
HC	hydrocarbon
HCFC	hydrochlorofluorocarbon
HFC	hydrofluorocarbon
HFO	hydrofluoroolefin
IDEA	International Database of Appliances
IEC	International Electrotechnical Commission
IGSD	Institute for Governance & Sustainable Development
ISEER	India seasonal energy efficiency ratio
ISO	International Organization for Standardization
JSRAE	Japan Society of Refrigerating and Air Conditioning Engineers
MEPS	minimum energy performance standards
METI	Ministry of Economy, Trade and Industry
$MTCO_2e$	metric tons of CO_2 equivalent
NEDO	New Energy and Industrial Technology Development Organization
R&D	research and development
RAC	room air conditioner
S&L	standards and labeling
SB	Senate Bill
SCOP	seasonal coefficient of performance
SHINE	Standards Harmonization Initiative for Energy Efficiency

SMUD	Sacramento Municipal Utility District
SNAP	Significant New Alternatives Program
VRF	variable refrigerant flow

Table of Contents

Abstract i

Table of Contents iv

Table of Tables vi

Executive Summary vii

1. Introduction 1

1.1 Background 1

1.2 Scope and Method 2

2. Barriers and Recommendations Related to Developing and Deploying High-Efficiency ACs with Low-GWP Refrigerants 3

2.1. Are there technological (related to energy efficiency) and economic barriers to developing and deploying high-efficiency ACs with low-GWP refrigerants? 3

2.1.1 Recommendations for overcoming technological and economic barriers 4

2.2. Are there other types of barriers to developing and deploying high-efficiency ACs with low-GWP refrigerants? 6

2.2.1 Recommendations for overcoming other types of barriers 8

2.3. Are there examples of AC market-transformation policies and programs designed for high energy efficiency and low GWP? 11

2.3.1 European Union: linking efficiency and GWP requirements, establishing high-GWP refrigerant quotas 12

2.3.2 Japan: transitioning to low-GWP refrigerants, pursuing further improvements via industry, government, and academic efforts 13

2.3.3 India: deploying ACs with flammable low-GWP refrigerant 13

2.3.4 China: planning for high efficiency with low-GWP refrigerants 14

2.3.5 California: incentivizing efficiency and low-GWP refrigerants 14

3. Summary 15

Acknowledgments.. 17

References... 18

Appendix A. Low-GWP Alternatives for Stationary Air Conditioning 23

Table of Tables

Table 1. Selected Standards for Refrigerants and Refrigeration Systems 10

Table 2. EcoDesign Requirements for Minimum Energy Efficiency in ACs (effective January 1, 2014) 12

Executive Summary

Because global air-conditioner (AC) demand is expected to increase significantly, particularly in emerging economies with hot climates, improving AC energy efficiency will be critical to reducing AC energy, cost (consumer lifecycle cost, electricity generation cost, etc.), peak load, and emissions impacts. At the same time, the phasedown of hydrofluorocarbon (HFC) refrigerants under the Kigali Amendment to the Montreal Protocol offers an opportunity to keep costs associated with energy efficiency improvement low by coordinating the transition to high efficiency with the HFC phasedown.

This report describes various types of barriers to the transition toward high-efficiency and low-GWP AC systems, based on interviews with experts as well as the most recent available data and literature. It also suggests solutions that might support the design of market-transformation programs to accelerate the adoption of such products. The barriers to improving energy efficiency while transitioning to low-GWP refrigerants for most ACs are primarily non-technical. Although changing refrigerants poses some technical challenges to AC manufacturers in having systems redesigned and facilities retrofitted to address safety issues related to flammable refrigerants, it also presents an opportunity to redesign ACs for higher efficiency or lower cost. Results from testing programs suggest low-GWP refrigerant alternatives can achieve higher efficiency compared with conventional high-GWP refrigerants in ACs even with limited system optimization.

Policy action can be accelerated by advancing the refrigerant transition and efficiency improvements simultaneously, with maximum coordination among government officials with jurisdiction over both types of policy. Policy solutions exist for overcoming the technological, economic, institutional, and informational barriers to higher energy efficiency and low-GWP refrigerants. The following are key policy recommendations to emerge from this study:

1) Stimulate the supply and demand needed to achieve economies of scale and identify cost-effective ways to realize the market transition
    i. Explore AC technical potential (maximum technologically feasible efficiency) and economic potential (efficiency achievable if all cost-effective, commercially available efficiency options were implemented)
    ii. Fill the gap in knowledge about unrealized opportunities to improve AC energy efficiency, adopt low-GWP refrigerants, and reduce prices, including further exploiting the non-energy or co-benefits of high-efficiency ACs (increased comfort, transmission and distribution loss reduction, benefits to disadvantaged communities, avoidance of rate subsidies, and so forth)
    iii. Improve financial incentive and procurement programs for energy efficiency with low-GWP criteria as well as market-based schemes (e.g., incentives to manufacturers)

iv. Enable small manufacturers to produce efficient ACs by helping build their research and development capacity, encouraging innovation through joint ventures with global manufacturers, or instituting other types of technology-transfer and capacity-building mechanisms

2) Establish appropriate standards and harmonize internationally
   i. Implement AC energy efficiency standards that consider low-GWP refrigerants as well as improvement of safety standards, including standards for storage, transport, installation, service, recycling or disposal, and building codes
   ii. Develop/improve safety standards, including training for production, installation, maintenance, and awareness, particularly on the use of flammable refrigerants
   iii. Update standards periodically to mitigate risk of obsolete technology being deployed in markets without updated standards or with later compliance dates
   iv. Harmonize national standards with international standards to help industry accelerate the refrigerant transition
   v. Close the gap between minimum energy performance standards (MEPS) and efficiencies of commercial available ACs
   vi. Implement seasonal performance metrics along with aggressive standards and labels to move ACs toward best product performance
   vii. Properly align regional energy efficiency program cycles
   viii. Raise public awareness (among consumers and small and local manufacturers) about policy and market trends driving the low-GWP transition as well as international standards being developed to ensure safety

3) Implement efficiency and refrigerant policies in parallel
   i. Implement low-GWP criteria when establishing or revising efficiency improvement policies
   ii. Consider mildly flammable and flammable refrigerants together at the planning stage and implement those plans in series or simultaneously
   iii. Improve market-transformation programs together for energy efficiency and low-GWP, such as standards, labeling, procurement, performance-assurance requirements for imports, and incentive programs, along with safety standards

1. Introduction

1.1 Background

Increasing incomes, electrification, and urbanization—as well as a warming world—are driving up global demand for air conditioners (ACs), particularly in emerging economies with hot climates. Recent studies estimate the global stock of room ACs (RACs) will exceed 1.5 billion units by 2030 and 2.5 billion by 2050, up from about 1 billion in 2015–2016 (IEA, 2018; Shah et al., 2015). Because AC energy consumption is expected to increase substantially, improving the energy efficiency of ACs will be critical to reducing their energy, lifecycle-cost, peak-load, and emissions impacts. At the same time, the non-ozone-depleting hydrofluorocarbon (HFC) AC refrigerants developed to replace their ozone-depleting predecessors—particularly hydrochlorofluorocarbons (HCFCs)—contribute significantly to climate change because of their high global warming potential (GWP).

On January 1, 2019, the Kigali Amendment to the Montreal Protocol came into force, establishing a global schedule for phasing down HFCs over the next 30 years. The need to increase AC efficiency and replace HFC refrigerants presents an ideal opportunity to accomplish both goals simultaneously. Previous research has quantified the energy and climate benefits of leapfrogging to high efficiency in tandem with the transition to low-GWP[1] refrigerants for RACs. Research also has highlighted opportunities for coordinating energy efficiency with refrigerant transition in the global RAC market, and it has identified the best-performing (i.e., most efficient and low-GWP-refrigerant using) RACs on the market (Park et al., 2017; Shah et al., 2017; Shah et al., 2015). WMO (2018) estimates that improving the energy efficiency of AC and refrigeration equipment during the transition to low-GWP refrigerants could double the climate benefits of the Kigali Amendment.

Various global manufacturers produce energy efficient RACs, including models with low-GWP refrigerants available in several economies.[2] The most efficient models are significantly more efficient (in terms of regional efficiency metrics) than the most efficient level recognized by energy efficiency standards and labeling (S&L) programs in the economies where the models are available (Park et al., 2017; Shah et al., 2013; Letschert et al., 2013). In addition, many studies have been addressing expected performance and safety issues due to switching from existing high-GWP refrigerants to low-GWP refrigerant alternatives in AC systems. However, few studies document

[1] We use the term "low-GWP" to mean "lower than the baseline refrigerant being replaced." The baseline refrigerants HCFC-22 (R-22), HFC-410A (R-410A), and HFC-134a (R-134a) have GWPs of 1,300 or higher (see Appendix A).
[2] According to Park et al. (2017), 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.

non-technical barriers to transitioning toward both high-efficiency and low-GWP refrigerant AC systems. This report summarizes challenges to developing and deploying high-efficiency and low-GWP AC systems, and it recommends policies that could facilitate this dual transition.

1.2 Scope and Method

This study focuses on RACs unless other AC systems are specified. We collected the information used in this study via a literature review and interviews with 14 experts from global AC manufacturers, refrigerant manufacturers, public institutions, and organizations related to research, equipment testing, and consulting. We conducted the interviews through in-person meetings, phone conversations, and emails. The identities of the interviewees, including three reviewers of earlier versions of the report, and their institutions—except those who requested anonymity—are acknowledged at the end of the report.

2. Barriers and Recommendations Related to Developing and Deploying High-Efficiency ACs with Low-GWP Refrigerants

Here we present barriers and recommendations related to developing and deploying high-efficiency ACs with low-GWP refrigerants.

2.1. Are there technological and economic barriers to developing and deploying high-efficiency ACs with low-GWP refrigerants?

***Technological perspective*:** There is an intrinsic gap between theoretical efficiency limits and the efficiencies that can be achieved by commercially available RAC products, mainly because the operation of real systems differs from the theoretical cycle in many ways: efficiency loss in the real-world compression process, heat transfer, and so forth. Although AC technologies are generally globally available, and there are no particular technological barriers to increased efficiency, relatively small or local manufacturers with limited research and development (R&D) capabilities may have limited access to certain advanced high-efficiency technologies that are proprietary or exclusively used by large global manufacturers. Such technologies include optimized system designs, high-efficiency compressors, high-efficiency heat exchangers, advanced control algorithms, and so forth. For example, China is the world's largest AC and compressor production base. A significant portion (over 50%) of AC compressor parts is imported into China, mainly from Japan, South Korea, and the United States.

There exists no single, ideal low-GWP AC refrigerant solution, because few refrigerants have chemical, environmental, thermodynamic, and safety properties suitable for use in AC systems (McLinden et al., 2017). Manufacturers must consider design changes to optimize AC systems by changing compressors and compressor oil, heat exchangers (to accommodate high-temperature glide), and expansion systems. Of these changes, only new compressor designs are identified as a significant technological barrier.

For alternative refrigerants, intellectual property issues would not be a significant barrier in the market transition. For example, R-32 and R-290 refrigerant using ACs are currently available. 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). Intellectual property issues were not a barrier during the transition from R-22 to R-410A. No patent exists for R-290 refrigerant production.

Economic perspective: High-efficiency AC products typically entail a temporary increase in upfront expenditure, compared with the price of low-efficiency products. Manufacturers often introduce such products by bundling high efficiency with other features such as occupancy sensors and humidity controls and by targeting premium markets, which further increases the initial price of these products relative to low-efficiency products. At the same time, because manufacturers frequently require short periods over which the incremental costs of high-efficiency products are projected to be paid back, the share of high-efficiency products on a market is typically much less than that of relatively low-efficiency products.

Transitioning to low-GWP refrigerants also entails upfront costs to AC manufacturers, including costs associated with system redesign R&D, retooled manufacturing lines, and retrofitting of manufacturing/test facilities to address safety issues related to flammable refrigerants. The material costs of alternative refrigerants may be higher (e.g., for hydrofluoroolefin [HFO] refrigerants) or lower (e.g., for R-32) than the costs of conventional refrigerants. However, the cost impact of refrigerants will depend, in the short term, on the relationship between supply (refrigerant) and demand (equipment using the refrigerant) and, in the long term, on economies of scale. Additional costs of materials or operation would include costs for new components (e.g., leak detectors, spark-free electric components), warranties, technician training, and consumer awareness.

To end users, insurance premiums might increase for homes and buildings with equipment that uses flammable refrigerants. Risks related to flammable refrigerants might require AC manufacturers to consider the liability associated with potential incidents and human injuries.

2.1.1 Recommendations for overcoming technological and economic barriers

To address the technological and economic barriers, it is important to stimulate the supply and demand needed to achieve economies of scale and identify cost-effective ways to realize the market transition. The following are recommended policy actions:

1. Explore and discuss technological barriers that refer to "technical potential," representing the energy efficiency that could be achieved if all commercially available efficiency options were implemented, or the maximum technologically feasible extent to which efficiency could be improved through technology diffusion.

   Specifically, many real RAC systems have a coefficient of performance (COP)—or energy efficiency ratio (EER, in units of W/W)[3]—in the range of 3–4. The highest-efficiency RAC models have a COP/EER in the range of 5–6, with fan power included, and a seasonal energy efficiency in the range of 5–12, depending on climatic conditions applied and test/calculation methods (Park et al., 2017). Although the highest-efficiency commercially available AC

[3] The International Organization for Standardization (ISO) Standard 5151 defines EER as the ratio of the total cooling capacity (CC) to the effective power input to the device at any given set of rating conditions, and it defines COP as the ratio of the heating capacity to the effective power input to the device at any given set of rating conditions. However, EER and COP have alternative definitions in certain regions.

models employ state-of-the-art efficiency technologies, wider adoption of these high-efficiency products is limited by factors related to markets, public policies, and other hindrances to technology diffusion.

2. Use consumer (i.e., end-user) economics to estimate the "economic potential" of high-efficiency ACs—that is, the efficiency achievable if all efficiency improvements were implemented that are (or are projected to be) cost-effective from the consumer point of view.

   For example, Shah et al. (2016) analyzed, for India, efficiency improvement potential, increases in retail AC prices, consumer bill savings over the lifetime of the ACs, consumer payback period, and the return on consumer investment given the bill savings, showing that the modest price increases required to cover the cost of efficiency result in significant bill savings and a short payback period. Abhyankar et al. (2017) calculated that if, starting in 2018, the average RAC efficiency in India improves by 6% per year, about 39 GW of peak load (equivalent to about 80 power plants of 500 MW each) and more than 64 terawatt-hours per year of energy could be saved by 2030. The net present value of the consumer benefit between 2018 and 2030 would range from US$600 million (in a price-increase scenario) to US$25 billion (in a no-price-increase scenario). Although there have been concerns about the rebound effect[4] that could reduce the financial benefit of efficiency improvements, the overall consumer welfare benefit would increase regardless of the effect (Chan and Gillingham, 2015; Borenstein, 2014).

3. Fill the gap in knowledge about unrealized opportunities to improve AC energy efficiency, adopt low-GWP refrigerants, and reduce prices.

   Unrealized opportunities may include further exploiting the non-energy or co-benefits of low-GWP high-efficiency ACs, for example, increased comfort, transmission and distribution loss reduction, benefits to disadvantaged communities, avoidance of rate subsidies, and so forth. In addition, redesigning ACs for use with low-GWP refrigerants could enable higher efficiency. 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). 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-290 or R-32 refrigerants, varying by manufacturer.

---

[4] Increasing AC efficiency could result in lower-than-expected energy savings if the improvement causes energy use to "rebound," for example, owing to consumers running their ACs more often or at colder temperatures.

Higher-efficiency products tend to have a wider range of market prices compared with lower-efficiency products, partly because high-efficiency models are often sold as premium products bundled with other non-energy features (Park et al., 2017). The price of high-efficiency products decreases as energy-efficient components achieve economies of scale. For example, Phadke et al. (2017) found that inflation-adjusted prices in RAC markets (e.g., Japan, South Korea, and India) have continued to fall over time, even with increases in efficiency.

4. Improve financial incentive and procurement programs for energy efficiency with low-GWP criteria as well as market-based schemes. Enable small manufacturers to produce efficient ACs by helping build their R&D capacity, encouraging innovation through joint ventures with global manufacturers, or instituting other types of technology-transfer and capacity-building mechanisms.

   Such policies will encourage manufacturers to improve AC performance further. Driven by advances in information technology and semiconductor manufacturing, the global AC market has moved rapidly towards variable-speed (i.e., inverter-driven) ACs across multiple product types. Transitioning manufacturing from inefficient fixed-speed ACs to efficient variable-speed ACs does not entail many changes to existing fixed-speed AC manufacturing lines beyond adding manufacturing capacity for semiconductor chips. A review of AC incentive programs in China, India, Indonesia, Mexico, and the United States found that such programs are particularly effective when they target emerging technologies that have low market penetration (de la Rue du Can et al., 2015). Incentive programs for manufacturers can help manufacturers reduce production costs via economies of scale and learning effects enabled by higher-volume production of emerging high-efficiency/low-GWP technologies—thus enabling policymakers to accelerate efforts aimed at deploying these technologies, particularly when the incentive is passed through to consumers.

2.2. Are there other types of barriers to developing and deploying high-efficiency ACs with low-GWP refrigerants?

***Market/technological/institutional perspective*:** Flammability risks are the most significant barrier to deploying low-GWP refrigerant ACs across multiple perspectives. Although R-32 and R-290 are used in commercially available RACs, R-32 may not be a long-term solution owing to its higher GWP compared with other alternative refrigerants (see Appendix A). To use R-290 (classified as flammable) in ACs, safety standards must consider a larger charge limit (the maximum amount of flammable refrigerant allowed in a product or system). Hence, flammability risks need further R&D efforts that develop alternative low-GWP AC refrigerants with attractive performance and risk characteristics, including lower-flammability refrigerants (such as R-452B, a blend containing R-125, R-1234yf, and R-32) and natural refrigerants.[5] Although comprehensive research and testing programs provide useful information on a wide range of low-GWP refrigerant candidates, such a wide range of options requires AC manufacturers to consider many technological, cost, and supply-chain scenarios (including the possibility of a few refrigerant suppliers dominating the market)—which increases uncertainty and risk for the manufacturers. Overall, the framework shaped by current institutions and technical knowledge may offer AC and refrigerant manufacturers little incentive to transition rapidly toward low-GWP ACs, mainly because of both refrigerant flammability issues and a lack of clear benefits stemming from the transition.

***Institutional/informational perspective*:** The connection between efficiency metrics and market-transformation policies in various regions has a major effect on the deployment of high-efficiency ACs. Seasonal energy efficiency metrics have been designed to estimate AC performance based on part- and full-load operation at multiple temperature conditions depending on climate. However, most developing economies still use the EER metric (non-seasonal), which hinders the introduction of high-efficiency variable-speed ACs. In addition, regional test standards adopting seasonal energy efficiency metrics vary by region or country; hence, manufacturers adopt different design strategies according to regional circumstances. Because it is difficult to directly compare one region's seasonal efficiency with another's, policymakers lack information on the global market's best-performing products. Such differences in energy efficiency standards and mismatches between industrial product-development cycles and some regional energy efficiency program cycles can hinder rapid deployment of high-efficiency ACs.

***Market/institutional/informational perspective*:** In some countries, minimum energy performance standards (MEPS) are very low compared with the average efficiency of ACs available on the market. For example, based on data from Lawrence Berkeley National Laboratory's International Database of Appliances (IDEA), about 89% of 335 models available in Indonesia have efficiencies equal to or greater than Indonesian EER (EER_{IDN})[6] 2.9, the ASEAN SHINE[7] requirement effective in 2020 (Park et al., 2017; Letschert et al., 2017). Indonesia's

---

[5] For example, the low-GWP alternative refrigerants evaluation program (AREP) of the Air-conditioning, Heating & Refrigeration Institute (AHRI) is an industry-wide cooperative research and testing program to identify suitable alternatives to high-GWP refrigerants. Reports from the program are available at http://www.ahrinet.org/arep. In Japan, the Japan Society of Refrigerating and Air Conditioning Engineers (JSRAE)—with support from the Ministry of Economy, Trade and Industry (METI) and the New Energy and Industrial Technology Development Organization (NEDO)—conducted a comprehensive risk assessment of mildly flammable refrigerants between 2011 and 2015, and it is conducting another risk assessment of flammable refrigerants.

[6] Indonesian S&L define EER_{IDN} as a weighted average of EER at full load (35°C) and EER at half load (35°C). For fixed-speed ACs, Indonesian EER is equivalent to the traditional EER we use throughout the study.

[7] 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 such as the Indonesian

average EER_{IDN} of 3.4 is much higher than its MEPS EER_{IDN} of 2.6. The highest-efficiency RAC has an EER of 5.7 and an EER_{IDN} of 6.16. Governments tend to set non-stringent MEPS mainly to protect small local manufacturers that might not be competitive against others in providing high-efficiency and low-price products. If local manufacturers can only meet MEPS, governments might still be justified in keeping MEPS low.

Public understanding of the transition to low-GWP ACs is also important. Addressing consumer concerns about flammability risks is important in particular. More broadly, public awareness (among consumers and small and local manufacturers) should be raised about policy and market trends driving the transition toward low-GWP refrigerants as well as the international standards being developed to ensure safety.

2.2.1 Recommendations for overcoming other types of barriers

To address the barriers discussed above, it is important to establish appropriate standards and harmonize internationally. The following are recommended policy actions:

1. Implement AC energy efficiency standards that consider low-GWP refrigerants as well as improvement of safety standards, including standards for production, storage, transport, installation, service, recycling or disposal, and building codes.

   In-depth understanding of the product- and building-level risks and risk-mitigation strategies are key to accelerating the market transition to low-GWP refrigerants. For example, in the United States, gas furnaces are typically found next to refrigerant lines, which could increase the potential to ignite the refrigerant. Proper AC installation by qualified technicians would be more important for flammable refrigerant equipment than for non-flammable refrigerant equipment, particularly in countries where contractors (rather than manufacturers) install AC systems. National/regional standards and regulations may need to consider quality-assurance programs such as technical training and certification. In addition, safety standards could require manufacturers or installers to add leak detectors to their AC systems and use spark-free electric components to address the flammability issue.

2. Update standards periodically to mitigate risk of obsolete technology being deployed in markets without updated standards or with later compliance dates, and harmonize national standards with international standards to help industry accelerate the refrigerant transition.

EER) of 2.9 (or a minimum cooling seasonal performance factor [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 16358-1.

In 2016, the Parties to the Montreal Protocol adopted the Kigali Amendment to the Montreal Protocol, which establishes a global schedule for phasing down HFC refrigerants. Countries (and sometimes regions within countries) have their own processes and timelines for development of standards.

In the United States, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has been leading the development of voluntary standards and guidelines that govern the application and use of all types of refrigerants. 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 several years. At present, several standards covering use of flammable refrigerants, charge limitation, and related equipment are available in IEC 60335-2-40, EN 378-1, and the latest UL 484 (see Table 1). The current charge limit for R-290 or any other flammable refrigerant is 150 g. If the allowable charge limit for safe use increases to 1 kg, the maximum capacity of mini-split units could reach 7 kW, which would enable RACs using R-290 to target 80% of the global market (Zeiger et al., 2014). Table 1 summarizes existing standards relevant to low-GWP refrigerants.

Table 1. Selected Standards for Refrigerants and Refrigeration Systems

Standard	Title	Recent update
ANSI/UL 60335-2-40 CAN/CSA-C22.2 No. 60335-2-40	2nd Ed. – aligned with IEC 60335-2-40 5th Ed. 3rd Ed. – aligned with IEC 60335-2-40 6th Ed.	2017
ASHRAE/ANSI Standard 34	Designation and Safety Classification of Refrigerants	2016
ASHRAE/ANSI Standard 15	Safety Standard for Refrigeration Systems	2016
EN-378-1	Refrigerating systems and heat pumps. Safety and environmental requirements. Basic requirements, definitions, classification and selection criteria	2016
IEC 60335-2-40	Household and similar electrical appliances - Safety - Part 2-40: Particular requirements for electrical heat pumps, air-conditioners and dehumidifiers (6th Ed.)	2018
ISO 817	Refrigerants - Designation and safety classification	2014
ISO 5149	Refrigerating systems and heat pumps - Safety and environmental requirements	2014
UL Standard 484	Standard for Room Air Conditioners	2014

Goetzler et al. (2010) provide a review of international/regional regulations and standards for the use of refrigerants in AC systems.

3. Encourage manufacturers to produce efficient ACs by closing the gap between MEPS and commercially available AC efficiencies, implementing seasonal performance metrics along with aggressive standards and labels to move ACs toward best product performance, and properly aligning regional energy efficiency program cycles.

   Even small local manufacturers could easily produce units that surpass existing MEPS in many developing economies. Adopting seasonal performance metrics, along with more stringent energy efficiency S&L (mandatory rather than voluntary), would promote deployment of high-efficiency, variable-speed RACs, by enabling manufacturers to further optimize AC performance for specific climate conditions (Park et al. 2017; Goetzler et al., 2016; Lord, 2013). Gallaher et al. (2017) noted that AC manufacturers differentiate their product lines by energy performance—the highest-priced (highest-profit-margin) product lines being the most efficient—pointing out the effect of stringent standards is to push manufacturers to incorporate the energy-efficient designs into lower-priced (lower-profit-margin), larger-market product lines sooner than they otherwise would. Stretch tiers for labels can recognize the contribution of some efficiency improvement options that are not fully captured by efficiency standards and existing test procedures. For example, variable-speed units with advanced system control algorithms could increase AC energy savings by 30%–40%,[8] but these savings are not fully captured by existing standards.

4. Raise public awareness (among consumers and small and local manufacturers) about policy and market trends driving the low-GWP transition as well as international standards being developed to ensure safety.

2.3. Are there examples of AC market-transformation policies and programs designed for high energy efficiency and low GWP?

The refrigerant transition has been an international effort driven by environmental concerns, while AC efficiency improvement typically has been driven by regional energy efficiency policies. However, because refrigerant and efficiency changes require redesigning AC systems and retooling manufacturing lines, coordinating the implementation of both types of changes can keep costs low for consumers, manufacturers, and utilities. Shah et al. (2015) found that implementing refrigerant transition and energy efficiency improvement policies in parallel for RACs roughly doubles the benefit of either policy implemented separately. Specifically, governments can do the following:

- Implement low-GWP criteria when establishing or revising efficiency improvement policies as, for example, the European Union (EU) has done.
- Consider mildly flammable and flammable refrigerants together at the planning stage, and implement those plans in series or simultaneously. For example, China and Japan have allowed mildly flammable refrigerants to be used in RACs and are considering market adoption of flammable refrigerants, while India has considered mildly flammable and flammable refrigerants at the same time.
- Improve financial incentive programs for energy efficiency and market-based schemes, such as emissions trading, so the industry can identify cost-effective ways to realize the market transition. For example, the EU has established high-GWP refrigerant quotas, and California recently launched a utility pilot program to incentivize use of low-GWP natural refrigerants in commercial refrigeration systems.

Here we present selected regional practices that provide insight for improving relevant policies.

---

[8] A literature review by Cheng and Lee (2016) showed that the energy-savings potential of ACs improved from 11% before 2000 to 30% after 2000 owing to advancements in sensor technologies.

2.3.1 European Union: linking efficiency and GWP requirements, establishing high-GWP refrigerant quotas

In the EU, Regulation (EU) No. 517/2014 requires an HFC phasedown. The EcoDesign Directive supports this phasedown by establishing lower MEPS for RACs that use low-GWP refrigerants (Table 2). Effective January 2025, the European Commission will ban refrigerants with GWP greater than 750[9] for residential split ACs with less than 3 kg of refrigerant charge.

Table 2. EcoDesign Requirements for Minimum Energy Efficiency in ACs (effective January 1, 2014)

		ACs, except double- and single-duct ACs		Double-duct ACs		Single-duct ACs	
CC	GWP	EU SEER	EU SCOP	EER	COP	EER	COP
< 6 kW	GWP > 150	4.60	3.80	2.60	2.60	2.60	2.04
	GWP ≤ 150	4.14	3.42	2.34	2.34	2.34	1.84
6–12 kW	GWP > 150	4.30	3.80	2.60	2.60	2.60	2.04
	GWP ≤ 150	3.87	3.42	2.34	2.34	2.34	1.84

SCOP = seasonal coefficient of performance
Source: Commission Regulation (EU) No.206/2012

Regulation (EU) No. 517/2014 also includes a quota for producers and importers placing at least 100 metric tons of CO_2 equivalent ($MTCO_2e$) of HFCs in bulk on the market in a calendar year (effective January 1, 2015). HFC pre-charged refrigeration, AC, and heat pump equipment are covered under the quota system effective January 1, 2017. In a recent report, the European Commission observed a general upward trend of prices since 2014, with a larger increase for HFCs with higher GWP (EC, 2017). The European Commission report also noted that the costs of obtaining authorizations for importing HFC equipment appear to be similar to bulk HFC price increases at the distributor level. EIA et al. (2018) found that this policy led to an HFC shortage and price increases of about €20/$MTCO_2e$ by December 2017. Midea, which has launched R-290 ACs in Europe, stated that the cost of addressing R-290 safety issues could be lower than the cost of purchasing the equivalent emissions allowances in a few years, given the increasing price (JARN, 2018).

[9] GWP is a measure of the radiative forcing of a pulse of emissions of a given greenhouse gas relative to the radiative forcing caused by an equal mass of carbon dioxide in the atmosphere; hence, it is unitless.

Further, the EcoDesign requirements shown above do not account for the fact that low-GWP refrigerants such as R-290 with GWP < 150 are actually more efficient than baseline refrigerants such as R-22 or R-410A. This has the unintended consequence of making the minimum efficiency requirements even *less stringent* (and therefore less effective) for such refrigerants. In the future, if such criteria for low-GWP refrigerants are developed, we recommend that the actual energy efficiency improvement (or reduction) be taken into account when setting the minimum energy efficiency requirements. In the case of the EU, this would imply that the EcoDesign requirements for GWP < 150 be set roughly 5%–10% higher than those for GWP > 150.

2.3.2 Japan: transitioning to low-GWP refrigerants, pursuing further improvements via industry, government, and academic efforts

Japanese manufacturers have been investing in alternative refrigerant R&D. Daikin launched the first R-32 RACs in 2012. Now nearly all RAC products and about 40% of commercial ACs in Japan have transitioned to R-32 (Okada, 2018; Park et al., 2017).

METI, NEDO, and JSRAE—together with academic and industrial partners—have led the comprehensive “Technology Development of High-efficiency Non-fluorinated Air-conditioning Systems” project to support development of high-efficiency equipment using low-GWP refrigerants, development of new high-efficiency/low-GWP refrigerants, and evaluation of the performance and safety of mildly flammable and flammable refrigerants (Suzawa, 2015).

2.3.3 India: deploying ACs with flammable low-GWP refrigerant

Flammable refrigerants (e.g., R-290) have not yet satisfied national safety standards in most countries, except for models with small CCs (and thus small charges). However, Deutsche Gesellschaftfur Internationale Zusammenarbeit (GIZ) has implemented R-290 RAC production in China and India, with more projects underway worldwide. In India, Godrej launched the first R-290 RAC models in 2012, resulting in cumulative sales of 120,000 units through the end of 2016 (Park et al., 2017). A recent study showed that R-290 is better suited than the high-GWP R-410A for use in hot climates, as a replacement for the R-22 refrigerant currently dominating India’s RAC market (Rajadhyaksha et al., 2013). Although the energy efficiency S&L for ACs do not favor low-GWP refrigerants, the most efficient current model uses R-290 to achieve an India seasonal energy efficiency ratio (ISEER) of 6.15, 37% higher than the highest S&L (5-Star) rating of ISEER 4.5.

2.3.4 China: planning for high efficiency with low-GWP refrigerants

In China, R-32 RACs are commercially available, but R-290 RACs are not. However, Chinese manufacturers—including Gree, Midea, Haier, and TCL—have completed retrofits of production lines for R-290 RACs and have registered R-290 RAC models for China's S&L program (Park et al., 2017). China is currently revising its RAC energy efficiency S&L, which could be improved by considering the efficiency improvement potential of low-GWP refrigerants.

2.3.5 California: incentivizing efficiency and low-GWP refrigerants

California has long been a U.S. leader in energy efficiency. Currently, California utilities offer approximately $1 billion in energy efficiency incentives each year (CPUC, 2016). With regard to low-GWP refrigerants, California's Senate Bill 1383 (SB 1383) requires the state to reduce HFC emissions by 40% below 2013 levels by 2030. Because the California Air Resources Board (CARB) estimated that California's HFC reductions related to Kigali Amendment compliance will only achieve 37%–48% of the total reductions required by SB 1383 (CARB, 2017), CARB adopted new regulations in March 2018 that prohibit new HFC use in the state. In addition, the Sacramento Municipal Utility District (SMUD) recently launched a first-of-its-kind utility pilot program to incentivize use of low-GWP natural refrigerants in commercial refrigeration systems. The program offers up to $150,000 for avoided greenhouse gas emissions at the rate of $25/MTCO$_2$e during a system lifetime (SMUD, 2017).

3. Summary

This report describes multiple types of barriers to the transition toward high-efficiency and low-GWP AC systems, based on interviews with experts as well as the most recent available data and literature. Some reports—including Goetzler et al. (2014), Colbourne et al. (2010), and ACRIB (2001)—discuss similar issues.

The barriers to improving energy efficiency while transitioning to low-GWP refrigerants for most ACs are primarily non-technical. Although changing refrigerants poses some technical challenges to AC manufacturers in having systems redesigned and facilities retrofitted to address safety issues related to flammable refrigerants, it also presents an opportunity to redesign ACs for higher efficiency or lower cost. Results from testing programs suggest low-GWP refrigerant alternatives can achieve higher efficiency compared with conventional high-GWP refrigerants in ACs even with limited or no further system optimization.

Deployment of high-efficiency ACs can be accelerated through appropriately designed policies such as more stringent S&L programs or incentive and procurement programs. The following are key policy recommendations to emerge from this study:

1. Stimulate the supply and demand needed to achieve economies of scale and identify cost-effective ways to realize the market transition by (a) exploring the technical and economic potential of high-efficiency ACs; (b) filling the gap in knowledge about unrealized opportunities to improve AC energy efficiency, adopt low-GWP refrigerants, and reduce prices; (c) improving financial incentive and procurement programs for energy efficiency with low-GWP criteria as well as market-based schemes; and (d) helping small manufacturers build their capacity to perform R&D and otherwise adopt innovative technologies.

2. Establish appropriate standards and harmonize internationally by (a) implementing AC energy efficiency standards that consider low-GWP refrigerants as well as improvement of safety standards; (b) developing/improving safety standards, including training for production, installation, maintenance, and awareness, particularly on the use of flammable refrigerants; (c) updating standards periodically to mitigate risk of obsolete technology being deployed in markets without updated standards or with later compliance dates; (d) harmonizing national standards with international standards to help industry accelerate the refrigerant transition; (e) closing the gap between MEPS and commercially available AC efficiencies; (f) implementing seasonal performance metrics along with aggressive standards and labels to move ACs toward best product performance; (g) properly aligning regional energy efficiency program cycles; and (h) raising public awareness (among consumers and small and local manufacturers) about policy and market trends driving the low-GWP transition as well as international standards being developed to ensure safety.

3. Implement efficiency and refrigerant policies in parallel by (a) implementing low-GWP criteria when establishing or revising efficiency improvement policies; (b) considering mildly flammable and flammable refrigerants together at the planning stage and implementing those plans in series or simultaneously; and (c) improving market-transformation programs together for energy efficiency and low-GWP, such as standards, labeling, procurement, performance-assurance requirements for imports, and incentive programs, along with safety standards.

Acknowledgments

The Institute for Governance & Sustainable Development (IGSD) funded this study. The authors thank a number of people who provided inputs, insights, comments, and/or data, including:

- Ashok Sarkar (World Bank)
- Balaji Natarajan (Multilateral Fund)
- Bassam Elassaad (Independent Consultant)
- Brian Holuj (United Nations Environment Programme)
- Chun-Cheng Piao (Daikin)
- Dae Hoon Kim, Jinho Yoo, and Hee Jeong Kang (Korea Refrigeration and Air-conditioning Assessment Center [KRAAC])
- Dietram Oppelt (HEAT International GmbH)
- Fabio Polonara (Università Politecnica delle Marche)
- Gabrielle Dreyfus (IGSD)
- Gregory Rosenquist (Lawrence Berkeley National Laboratory [LBNL])
- Iain Campbell (Rocky Mountain Institute)
- Jun Young Choi (Korea Testing Laboratory [KTL])
- Shaofeng Hu (United Nations Environment Programme)
- Omar Abdelaziz (Clean Energy Air and Water Technologies, FZE)
- Philipp Munzinger and Philipp Denzinger (Deutsche Gesellschaft für Internationale Zusammenarbeit [GIZ] GmbH)
- Qiao Lu (B/E Aerospace)
- Shaobo Jia (Heatcraft)
- Samuel Yana Motta (Honeywell)
- Tetsuji Okada (Japan Refrigeration and Air Conditioning Industry Association [JRAIA])
- Zidu Ma (Carrier)

We also thank Elizabeth Coleman for the administrative support, and Jarett Zuboy for editing support. Any errors or omissions are the authors' own.

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*. 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., 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.

ACRIB (Air Conditioning and Refrigeration Industry Board). 2001. *Guidelines for the Use of Hydrocarbon Refrigerants in Static Refrigeration and Air Conditioning Systems*. Carshalton, UK: ACRIB. https://www.logic4training.co.uk/?wpfb_dl=23

Borenstein, S. 2014. *A Microeconomic Framework for Evaluating Energy Efficiency Rebound and Some Implications*. EI @ Haas WP 242R. Berkeley CA: The Energy Institute at Haas.

CARB (California Air Resources Board). 2017. *Potential Impact of the Kigali Amendment on California HFC Emissions - Estimates and Methodology used to Model Potential Greenhouse Gas Emissions Reductions in California from the Global Hydrofluorocarbon (HFC) Phase-down Agreement of October 15, 2016, in Kigali, Rwanda ("Kigali Amendment")*. Sacramento: CARB. https://www.arb.ca.gov/cc/shortlived/CARB-Potential-Impact-of-the-Kigali-Amendment-on-HFC-Emissions-Final-Dec-15-2017.pdf

Chan, N.W., and K. Gillingham. 2015. "The Microeconomic Theory of the Rebound Effect and Its Welfare Implications." *Journal of the Association of Environmental and Resource Economists* 2(1): 133–159.

Cheng, C-C, and D. Lee. 2016. "Enabling Smart Air Conditioning by Sensor Development: A Review." *Sensors* 16: 2028, DOI:10.3390/s16122028.

Colbourne, D., R. Huehren, B. Schrempf, L. Ederberg, and S. Meenen. 2010. *Guidelines for the Safe Use of Hydrocarbon Refrigerants: A Handbook for Engineers, Technicians, Trainers* *and Policy-Makers—for a Climate-Friendly Cooling*. Bonn and Eschborn: Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH.

CPUC (California Public Utilities Commission). 2016. *Regulating Energy Efficiency: A Primer on the CPUC's Energy Efficiency Programs*. San Francisco: CPUC. http://www.cpuc.ca.gov/uploadedFiles/CPUC_Public_Website/Content/News_Room/Fact_Sheets/English/Regulating%20Energy%20Efficiency%200216.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/

de Larminat, P., and A. Wang. 2017. "Overview of Fluids for AC Applications." *ASHRAE Journal*, February. http://www.johnsoncontrols.com/-/media/jci/be/united-states/specialty-pages/files/be_article_ashrae_overviewfluidsacapplications.pdf?la=en

de la Rue du Can, S., G. Leventis, N. Shah, and M. McNeil. 2015. *Cooling the Growth of Air Conditioners Energy Consumption*. LBNL-184253. Berkeley, CA: Lawrence Berkeley National Laboratory. http://eta-publications.lbl.gov/sites/default/files/lbnl-184253.pdf

EC (European Commission). 2017. *Report from the Commission Assessing the Quota Allocation Method in Accordance with Regulation (EU) No 517/2014*. Brussels: EC. https://ec.europa.eu/clima/sites/clima/files/f-gas/legislation/docs/com_2017_377_en.pdf

EIA (Environmental Investigation Agency), Climate Advisers Network, ECOS, ECODES, Legambiente, and ZERO. 2018. *Recommendations for Making the EU F-Gas Regulation a Success*. Brussels: EC. https://ec.europa.eu/clima/sites/clima/files/docs/0106/2018_03_06_eia_en.pdf

Gallaher, M., T. Scott, Z. Oliver, K. Clark-Sutton, and B. Anderson. 2017. *Benefit-Cost Evaluation of U.S. Department of Energy Investment in HVAC, Water Heating, and Appliance Technologies*. Prepared by RTI International for the U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2017/09/f36/DOE-EERE-BTO-HVAC_Water%20Heating_Appliances%202017%20Impact%20Evaluation%20Final.pdf

Goetzler, W., J. Burgos, H. Hiraiwa, and T. Sutherland. 2010. *Review of Regulations and Standards for the Use of Refrigerants with GWP Values Less than 20 in HVAC&R Applications*. Navigant Consulting, Inc. http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/Technical%20Results/ARTI-Rpt-09001-01.pdf

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

Goetzler, W., T. Sutherland, M. Rassi, and J. Burgos. 2014. *Research & Development Roadmap for Next-Generation Low Global Warming Potential Refrigerants*. Prepared by Navigant Consulting, Inc. for the U.S. Department of Energy. https://www.energy.gov/sites/prod/files/2014/12/f19/Refrigerants%20Roadmap%20Final%20Report%202014.pdf

IEA (International Energy Agency). 2018. *The Future of Cooling Opportunities for Energy-Efficient Air Conditioning*. Paris: IEA. http://www.iea.org/publications/freepublications/publication/The_Future_of_Cooling.pdf

JARN (*Japan Air Conditioning, Heating and Refrigeration News*). 2018. "Midea Strongly Promotes R290 ACs Targeting Environmental Challenges." *JARN News*, April 27, 2018. http://www.ejarn.com/detail.php?id=51006&l_id=

Letschert, V., L.B. Desroches, J. Ke, and M. McNeil. 2013. "Energy Efficiency - How Far Can We Raise the Bar? Revealing the Potential of Best Available Technologies." *Energy* 59: 72–82. https://doi.org/10.1016/j.energy.2013.06.067

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.

Lord, R. 2013. "HVAC Technologies for Building Energy Efficiency Improvements." Presented at the 2013 National Symposium on Market Transformation. http://aceee.org/files/pdf/conferences/mt/2013/Richard%20Lord_2B.pdf

McLinden, M.O., J.S. Brown, R. Brignoli, A.F. Kazakov, and P.A. Domanski. 2017. "Limited Options for Low-Global-Warming-Potential Refrigerants." *Nature Communications* 8: 14476.

Okada, T. 2018. "Transitioning to Alternatives and Challenges in Japan." Presented at the ATMOsphere Japan 2018, February 13, 2018. http://www.atmo.org/presentations/files/5a826c5dc6f591518496861JzRit.pdf

OTS (Optimized Thermal Systems, Inc.). 2016. *An Evaluation of R32 for the US HVAC&R Market*. Beltsville, MD: OTS.

http://www.optimizedthermalsystems.com/images/pdf/about/An-Evaluation-of-R32-for-the-US-HVACR-Market.pdf

Park, W., N. Shah, and B. Gerke. 2017. *Assessment of Commercially Available Energy-Efficient Room Air Conditioners Including Models with Low Global Warming Potential (GWP) Refrigerants*. LBNL-2001047. Berkeley, CA: Lawrence Berkeley National Laboratory. https://eta.lbl.gov/sites/default/files/publications/assessment_of_racs_lbnl-_2001047.pdf

Phadke, A., W. Park, N. Abhyankar, and N. Shah. 2017. "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.

Rajadhyaksha, D., A. Sahu, B.J. Wadia, and D. Colbourne. 2013. "HC-290 as an Alternative Refrigerant for Split Air Conditioning Systems in High Ambient Temperatures." Presented at the UNIDO ATMOsphere Technology Summit, June 3–4, Vienna.

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

Shah, N., N. Abhyankar, W. Park, A. Phadke, S. Diddi, D. Ahuja, P.K. Mukherjee, and A. Waila. 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. https://ies.lbl.gov/publications/cost-benefit-improving-efficiency

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*. LBNL-2001021. Berkeley, CA: Lawrence Berkeley National Laboratory. https://eta.lbl.gov/sites/default/files/publications/lbnl-2001021.pdf

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

SMUD (Sacramento Municipal Utility District). 2017. *SMUD Pilot Natural Refrigerant Incentive Program – Program Summary*. Rev 5/17. Sacramento: SMUD.

https://www.smud.org/-/media/Documents/Business-Solutions-and-Rebates/Refrigerant-Pilot-Program-Summary.ashx?la=en&hash=E6C236B76B309F7FCE2039BFA36198A5A4F3564A

Suzawa, M. 2015. "Overview of the NEDO-Project - Technology Development of High-efficiency Non-fluorinated Air-conditioning Systems." New Energy and Industrial Technology Development Organization (NEDO). https://www.jsrae.or.jp/committee/binensei/1.2Suzawa.pdf

WMO (World Meteorological Organization). 2018. Scientific Assessment of Ozone Depletion: 2018. Global Ozone Research and Monitoring Project–Report No. 58, 588 pp., Geneva, Switzerland, 2018. https://ozone.unep.org/sites/default/files/Assessment_Panel/SAP-2018-Assessment-report.pdf

Zeiger, B., B. Gschrey, and W. Schwarz. 2014. *Alternatives to HCFCs/HFCs in Unitary Air Conditioning Equipment at High Ambient Temperatures*. Frankfurt: Öko-Recherche. https://ec.europa.eu/clima/sites/clima/files/f-gas/legislation/docs/alternatives_high_gwp_annex_en.pdf

Appendix A. Low-GWP Alternatives for Stationary[10] Air Conditioning

Table A1. Examples of Low-GWP Alternatives for Stationary ACs

Type	Chemical	Safety Class[a]	GWP[b]	Flamma-bility[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 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.
Hydrocarbons (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 from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change.

[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: de Larminat and Wang (2017), Seidel et al. (2016)

[10] 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).