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BUILDING TECHNOLOGIES OFFICE





The Future of Air Conditioning for Buildings

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W. Goetzler, M. Guernsey, J. Young, J. Fuhrman
Navigant Consulting, Inc.

O. Abdelaziz, PhD
Oak Ridge National Laboratory

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Prepared for:
U.S. Department of Energy
Office of Energy Efficiency and Renewable Energy
Building Technologies Office
eere.energy.gov/buildings

Prepared by:
Navigant Consulting, Inc.
77 South Bedford Street, Suite 400
Burlington, MA 01803

William Goetzler
Matt Guernsey
Jim Young
Jay Fuhrman

Oak Ridge National Laboratory
Oak Ridge, TN 37831

Omar Abdelaziz, PhD

List of Acronyms

A/C	Air Conditioning
AHRI	Air Conditioning, Heating, and Refrigeration Institute
AREP	AHRI's Low-GWP Alternative Refrigerant Evaluation Program
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BTO	Building Technologies Office (Department of Energy, part of EERE)
CAC	Residential Central Air Conditioner
CFC	Chlorofluorocarbon
CDD	Cooling Degree Days
CO_2	Carbon Dioxide
COP	Coefficient of Performance
CRAC	Computer Room Air Conditioner
DOE	U.S. Department of Energy
EER	Energy Efficiency Ratio
EERE	U.S. DOE's Office of Energy Efficiency and Renewable Energy
EEV	Electronic Expansion Valve
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HAT	High Ambient Temperature Test Conditions
HC	Hydrocarbon
HCFC	Hydrochlorofluorocarbon
HFC	Hydrofluorocarbon
HFO	Hydrofluoroolefin
HVAC	Heating, Ventilation, and Air-Conditioning
IEA	International Energy Agency
IECC	International Energy Conservation Code
IEER	Integrated Energy Efficiency Ratio
IPCC	Intergovernmental Panel on Climate Change
IT	Information Technology
LBNL	Lawrence Berkeley National Laboratory (U.S.)
kWh	Kilowatt-hour
kW_{th}	Kilowatt (refrigeration capacity)
MW	Megawatt
NIST	National Institute for Standards and Technology (U.S.)
NVC	Non-Vapor Compression
O&M	Operations and Maintenance
ODP	Ozone Depletion Potential
ODS	Ozone Depleting Substance

OECD	Organization of Economic Coordination and Development
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory (U.S.)
PTAC	Packaged Terminal Air Conditioner
PTHP	Packaged Terminal Heat Pump
PV	Solar Photovoltaics
R&D	Research and Development
RT	Refrigeration Ton
RTU	Rooftop Unit
SEER	Seasonal Energy Efficiency Ratio
SNAP	EPA's Significant New Alternatives Policy Program
TXV	Thermal Expansion Valve
UN	United Nations
UNEP	United Nations Environment Programme
VRF	Variable Refrigerant Flow

Executive Summary

The Building Technologies Office (BTO), within the U.S. Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy, works with researchers and industry to develop and deploy technologies that can substantially reduce energy consumption and greenhouse gas (GHG) emissions in residential and commercial buildings. Air conditioning (A/C) systems in buildings contribute to GHG emissions both directly through refrigerant emissions, as well as indirectly through fossil fuel combustion for power generation. BTO promotes pre-competitive research and development (R&D) on next-generation HVAC technologies that support the phase down of hydrofluorocarbon (HFC) production and consumption, as well as cost-effective energy efficiency improvements.

Over the past several decades, product costs and lifecycle cooling costs have declined substantially in many global markets due to improved, higher-volume manufacturing and higher energy efficiency driven by R&D investments and efficiency policies including minimum efficiency standards and labeling programs.[1] This report characterizes the current landscape and trends in the global A/C market, including discussion of both direct and indirect climate impacts, and potential global warming impacts from growing global A/C usage. The report also documents solutions that can help achieve international goals for energy efficiency and GHG emissions reductions. The solutions include pathways related to low-global warming potential[2] (GWP) refrigerants, energy efficiency innovations, long-term R&D initiatives, and regulatory actions.

DOE provides, with this report, a fact-based vision for the future of A/C use around the world. DOE intends for this vision to reflect a broad and balanced aggregation of perspectives. DOE brings together this content in an effort to support dialogue within the international community and help keep key facts and objectives at the forefront among the many important discussions.

Expected Growth in A/C Demand

Today, A/C equipment represents close to a $100 billion, 100 million-unit per year global market, and accounts for 4.5 exajoules (4.26 Quadrillion Btus) of site energy consumption per year[3], comprising just over 4% of global building site-energy consumption.[4] While adoption of A/C in developed countries increased rapidly in the 20th century, the 21st century will see greater adoption in developing countries, especially those in hot and (possibly) humid climates with large and growing populations, such as India, China, Brazil, and Middle Eastern nations. The International Energy Agency (IEA) projects that A/C energy consumption by 2050 will increase 4.5 times over 2010 levels for non-Organization of Economic Coordination and Development

[1] R. D. Van Buskirk, et al. 2014. "A Retrospective investigation of energy efficiency standards: policies may have accelerated long term declines in appliance costs." Lawrence Berkeley National Laboratory. Available: http://eetd.lbl.gov/publications/a-retrospective-investigation-of-ener

[2] Refers to the amount of heat a greenhouse gas traps in the atmosphere over a specified timeframe, relative to the same mass of CO_2. This report uses 100-year GWP values from the IPCC Fifth Assessment Report.

[3] Source or primary energy consumption is approximately 3x site electricity consumption globally or 13.5 EJ (12.8 Quads. International Energy Agency. 2013. "Transition to Sustainable Buildings: Strategies and Opportunities to 2050." Figure 1.5. OECD/IEA. Available at: https://www.iea.org/media/training/presentations/etw2014/publications/Sustainable_Buildings_2013.pdf

[4] International Energy Agency. 2013. "Transition to Sustainable Buildings: Strategies and Opportunities to 2050." OECD/IEA. Available at: https://www.iea.org/media/training/presentations/etw2014/publications/Sustainable_Buildings_2013.pdf

(OECD) countries versus 1.3 times for OECD countries.[4] Rising income and greater access to A/C equipment in many of these nations opens the door to building cooling for billions of people, which will provide significant benefits in increased human health and comfort.

Global Warming Contributions

Globally, stationary A/C systems account for nearly 700 million metric tons of direct and indirect CO_2-equivalent emissions ($MMTCO_2e$) annually. Indirect emissions from electricity generation account for approximately 74% of this total, with direct emissions of HFC and hydrochlorofluorocarbon (HCFC) refrigerants accounting for 7% and 19%, respectively.[5,6] While electricity consumption is the largest driver of GHG emissions from A/C (i.e., indirect impacts), emissions of HCFC and HFC refrigerants have a disproportionately large global warming impact relative to their mass. Addressing direct emissions therefore offers an important path to substantially reducing A/C GHG emissions.

Transitioning to low-GWP refrigerants could eliminate the vast majority of direct emissions from A/C systems. With many available low-GWP alternative refrigerants having GWPs of 100 or less, industry has the opportunity to implement high-impact solutions for all applications. A theoretical 100% adoption of near-zero GWP refrigerants could reduce annual global A/C emissions by up to 26%, assuming no changes in efficiency. With preliminary testing indicating the potential for efficiency improvements for equipment using low-GWP refrigerants, reductions to indirect emissions are possible as well, especially if high-efficiency equipment adoption is incentivized globally through efficiency standards and labeling programs. Given the refrigerant options available today, DOE sees opportunity to reduce global A/C GHG emissions by 20% or more (75% or more of all direct emissions). Such a transition could occur in as short as a single turnover cycle of installed equipment, and would limit direct emissions growth, especially in markets that lack effective refrigerant management programs. In addition to a transition to low-GWP refrigerants, reducing emissions during initial charging, servicing, and end-of-life disposal could help further mitigate direct emissions. Deeper reductions in emissions are possible in the long-term from lower-GWP refrigerants and improved efficiency.

Without action by the international community, the expected demand for A/C in developing countries in the coming decades will substantially increase global GHG emissions. Rising global temperatures resulting from climate change will only exacerbate the problem by increasing A/C demand and contributing to further climate change. These impacts will go unchecked unless the international community takes steps to reduce direct and indirect emissions from A/C usage. The transition of Article 5 nations (as defined under the Montreal Protocol) from ozone-depleting, high-GWP HCFCs presents the opportunity to significantly reduce direct climate impacts by avoiding the uptake of high-GWP HFCs and transitioning directly to low-GWP alternatives. Given the importance of both efficiency and refrigerant emissions, the total life cycle climate impacts of A/C systems, i.e., both direct and indirect emissions, should be considered when evaluating approaches to transition from high-GWP refrigerants.

[5] This analysis relies upon energy consumption and emissions data from the U.N.'s Intergovernmental Panel on Climate Change, U.S. EPA, World Bank, and the Proceedings of the National Academy of Sciences.
[6] Estimations of direct and indirect impacts are subject to significant uncertainty and depend heavily upon annual and end-of-life leakage rates, local climate, and electricity generation mix.

Development of Low-GWP A/C Systems

The A/C industry has a long history of proactively engaging and helping to meet environmental goals through international cooperation and technology innovation. Manufacturers successfully developed products to transition away from ozone-depleting refrigerants and continually innovate to deliver lower cost products with higher efficiency and performance. Non-ozone-depleting HFCs and HFC blends (e.g., R-410A and R-134a) have replaced HCFC and CFC refrigerants and now dominate the industry in developed countries. However, the GWPs of today's most common refrigerants are over a thousand times more powerful than the most prevalent GHG, carbon dioxide.

Products using low-GWP refrigerants and having comparable or improved efficiency relative to today's typical equipment are already commercially available in four key equipment categories, including for ductless split systems, which are by far the largest market segment. (See Table ES-1). For the remaining categories, energy-efficient products using low-GWP refrigerants are in varying stages of testing and development.

Many products that are currently available, or will become available in the near-term, provide GWP reductions of 50-75% or more compared to the most commonly used refrigerants. For example, manufacturers have debuted small, self-contained equipment using R-32, an HFC with a GWP of 677 that replaces R-410A (GWP=1,924),[7] and chillers using R-1234ze, a hydrofluoroolefin (HFO) with a GWP of less than 1 that replaces R-134a (GWP=1,300).[8] Standards organizations, government bodies, and other stakeholders are working together to expedite the revision of relevant safety standards and building codes to ensure the safe use of A/C systems using low-GWP refrigerants.[9]

Table ES-1: Status of A/C Equipment Categories with Low-GWP Refrigerant Options Showing Comparable or Improved Performance and Efficiency[10]

Residential	Status	2012 Global Annual Sales (US$B)	Commercial	Status	2012 Global Annual Sales (US$B)
Room & portable	● (green)	$3.4	Packaged terminal	◕ (blue)	$0.2
Ducted split & single-package	◔ (blue)	$3.3	Packaged rooftop unit	◔ (blue)	$4.6
Ductless split system	● (green)	$48.5	Ductless (VRF/VRV)	◕ (blue)	$10.7
			Scroll / recip. chiller	◕ (blue)	
			Screw chiller	● (green)	$8.3 (All chillers)
			Centrifugal chiller	● (green)	

Green signifies that equipment operates using refrigerants with GWP as low as 10 or less
Blue signifies that equipment operates using refrigerants with GWP as low as 700 or less

● Commercially available in some global markets; ◕ Product under development; ◔ Tested in Lab

[7] Daikin. 2015. "White House Recognizes Air Conditioner and Chemical Manufacturer Daikin for Commitment to Reduce Greenhouse Gas Emissions." Press Release. http://www.daikin.com/press/2015/151016/.
[8] Cooling Post. 2016. "Climaventa Adds 1234ze Chiller." Accessed June 2016. Available at: http://www.coolingpost.com/world-news/climaventa-adds-1234ze-chiller/.
[9] ASHRAE. 2016. "ASHRAE, AHRI, DOE Partner to Fund Flammable Refrigerant Research." Accessed June 2016. Available at: https://www.ashrae.org/news/2016/ashrae-ahri-doe-partner-to-fund-flammable-refrigerant-research.
[10] Table ES-1 summarizes information in Table 4-7; refer to the latter for additional details and references.

Much of the R&D required before commercialization of some applications of alternative refrigerants, such as split and packaged central A/Cs, is already underway. Changing refrigerants requires system design changes before a product can be commercialized; even for refrigerants that industry deems as "drop-in" replacements, small refinements are needed, such as refrigerant-charge optimization and adjusting the size of the thermal expansion device. The level of engineering work required varies significantly by application and refrigerant choice. The R&D optimizes tradeoffs between GWP, performance, efficiency, flammability, and cost relative to current refrigerants.

To understand how different refrigerant alternatives affect the capacity and efficiency of common A/C equipment categories, the Air Conditioning, Heating, and Refrigeration Institute (AHRI) led an international group of manufacturers that conducted a series of tests known as the Low-GWP Alternative Refrigerants Evaluation Program (Low-GWP AREP). Oak Ridge National Laboratory (ORNL) conducted testing of several low-GWP refrigerants as part of Low-GWP AREP on a 5.25 kW_{th} (1.5 ton) ductless mini-split A/C system designed for the most widely used refrigerant, R-410A. The results showed that with modest design optimization, most of these refrigerants provided similar or improved efficiency (-8% to +6%) and capacity (-16% to +13%) compared to R-410A in both moderate and high ambient temperature conditions.[11] These results are encouraging because they suggest the potential for both direct and indirect GHG emissions reductions, as well as reduced operating costs due to higher efficiency. With full-system optimization for low-GWP refrigerants, further efficiency and capacity improvements over current systems are expected.

Advances in A/C System Efficiency

In addition to advancing low-GWP refrigerants, it is also essential that the energy efficiency of A/C systems continue to improve to maximize GHG emissions reductions. The A/C industry has steadily improved the energy efficiency of A/C systems through a combination of technological innovation and market transformation strategies. From 1990 to 2013, U.S. shipment-weighted efficiency for residential split-system A/Cs increased from 9.5 SEER (~2.2 COP) to 14.9 SEER (~3.8 COP).[12,13] Manufacturers made these improvements through the introduction of many individual technologies that collectively improve overall system efficiency, including: multi- and variable-speed drives, novel compressor, fan, motor, and heat exchanger designs, electronic expansion valves, and advanced controls.

Government and industry programs have significantly increased adoption of high efficiency A/C systems through minimum efficiency standards, comparative and endorsement labels (e.g., ENERGY STAR), public challenges and awards, and incentive programs. These programs result

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[11] Schultz, Ken. 2016. "Summary of High Ambient Temperature (HAT) Tests Conducted Under AREP II." In Orlando, Florida. http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP_II/REF-3_HAT_Summary_Ingersol_Rand.pdf, http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP_Final_Reports/AHRI_Low_GWP_AREP_Rpt_056.pdf.
[12] Original data in SEER; conversion is solely for conveying approximate impact to international audiences, but is generally considered to be an imprecise conversion. Cooling SEER to EER estimated using de-rating estimates from Table 6 of Cutler et al. (2013) and EER to COP conversion factor of EER = 3.412 COP. Exact SEER to EER/COP conversions vary depending on local climate. Cutler et al. 2013. "Improved Modeling of Residential Air Conditioners and Heat Pumps for Energy Calculations." NREL/TP-5500-56354. NREL. http://www.nrel.gov/docs/fy13osti/56354.pdf.
[13] Groff, Gerald. 2014. "Heat Pumps in North America 2014." IEA/OECD Heat Pump Centre Newsletter. Vol. 32, No. 3. 2014. Available at: http://www.nachhaltigwirtschaften.at/iea_pdf/newsletter/iea_hpc_newsletter_no_3_2014.pdf.

in significant emissions reductions and cost savings for consumers.[14] In the U.S., updated efficiency standards published by DOE at the end of 2015 for commercial HVAC systems are expected to save more energy than any other standard issued by DOE to date.[15] In June of 2016, the Clean Energy Ministerial (CEM) launched an Advanced Cooling Challenge with the support of numerous governments, manufacturers, and non-profit groups, which aims to improve average A/C system efficiency by 30% by 2030. Comprehensive approaches that combine efficiency with effective refrigerant management practices, high-performance building design, and renewable energy integration will be the most effective means of reducing both direct and indirect A/C emissions going forward.

Cost Implications of Refrigerant Transitions

One of the key objectives in the transition to sustainable A/C is the development of innovations that are cost-effective globally. Historically, the A/C industry has used innovation and cooperation to adapt and meet environmental and energy efficiency goals while providing safe, reliable, and cost-effective products. For example, since the 1970s, U.S. manufacturers have steadily reduced the inflation-adjusted cost of residential central ducted A/C systems while maintaining or improving performance, even while transitioning away from ozone depleting substances (ODS) to today's HFC refrigerants (see Figure 6-1). The relatively small contribution of refrigerant costs to lifecycle A/C system costs implies that initial cost increases because of a low-GWP refrigerant transition should be manageable (See Figure ES-1). Efficiency improvements and charge reductions that are likely to coincide with the transition to low-GWP refrigerants can mitigate, through lifecycle efficiency savings, increases in up front purchase costs to consumers resulting from more expensive refrigerants and system redesigns.

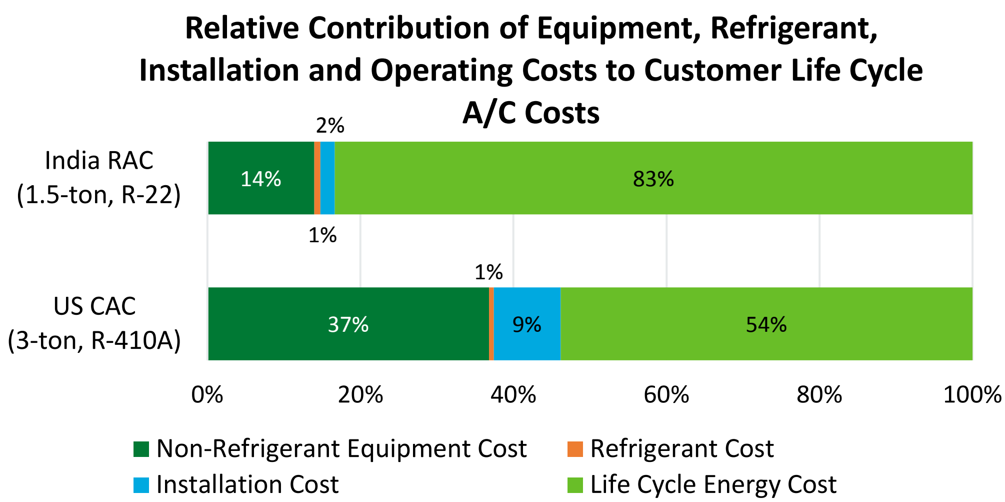

Figure ES-1: Residential life cycle A/C cost breakdown examples[16]

[14] DOE. 2016. "Saving Energy and Money with Appliance and Equipment Standards in the United States." http://energy.gov/sites/prod/files/2016/02/f29/Appliance%20Standards%20Fact%20Sheet%20-%202-17-2016.pdf. Efficiency standards and projected energy savings include commercial air-cooled air conditioners, heat pumps, and warm air furnaces.
[15] DOE. 2016. "Energy Department Announces Largest Energy Efficiency Standard in History." http://energy.gov/articles/energy-department-announces-largest-energy-efficiency-standard-history
[16] For full explanation of sources and assumptions, see Figure 6-2

In spite of cost-offsets due to efficiency improvements, up-front cost premiums for new products are a potential concern as they could dissuade some consumers from replacing older less efficient models with newer high-efficiency units, even if lifecycle costs are similar or lower due to energy efficiency gains. This could hinder the broad adoption needed to meet international GHG goals. Cost projections are currently uncertain for both the low-GWP refrigerants and for the associated transitional engineering investments. Refrigerant costs may not increase for systems that use refrigerants currently in mass production, such as R-32 and hydrocarbons. However, new, more complex molecules, such as HFOs, are expected to be more expensive.[17] Added cost may also come, at least initially, in systems that necessitate specialized component designs, increased heat exchanger size, higher operating pressures, or additional safety measures for flammable refrigerants. Nevertheless, performance test results of alternative refrigerants suggest that the cost barrier is addressable through both manufacturing advances and efficiency improvements that reduce lifecycle costs. Moreover, policies ranging from demand-side management incentives to minimum standards and labeling programs can help encourage development and deployment of energy efficient and climate friendly options that reduce lifecycle costs to consumers.

Next-Generation A/C Systems

Over the next several decades, A/C systems will transition to using low-GWP refrigerants, including synthetic substances such as HFOs and lower-GWP HFCs, as well as non-fluorinated fluids such as hydrocarbons. Some A/C systems may transition to entirely different technologies that move beyond vapor compression technology altogether, while maintaining or improving efficiency. Table ES-2 highlights some of the advanced technologies under development today. The long-term vision of how and where these technologies are applicable constantly evolves as researchers continue to redefine what is possible through new material discoveries, innovative approaches, or adapting technologies from other industries.

Table ES-2: Next-Generation A/C Technology Research Areas

Barrier	Description	Examples
Advanced Vapor-Compression Systems	A/C technologies that significantly lower refrigerant GWP and energy consumption for vapor-compression A/C systems while maintaining cost-competitiveness with today's high-volume equipment.	• Low-GWP refrigerants (e.g., natural refrigerants and synthetic olefins) • Climate-specific designs
Emerging Non-Vapor-Compression (NVC) Systems	A/C systems that do not rely on refrigerant-based vapor-compression systems and can provide energy savings with high-volume cost similar to today's state-of-the-art.	• Solid-State (thermoelectric, magnetocaloric) • Electro-mechanical (evaporative, thermoelastic) • Thermally driven (absorption)
Integration of A/C and Other Building Systems	A/C systems that share excess heat and other resources with other systems to provide energy savings for the entire building.	• Capturing waste energy from space cooling for water heating and dehumidification

[17] McLinden et al. 2014. "A Thermodynamic Analysis of Refrigerants: Possibilities and Tradeoffs for Low-GWP Refrigerants." International Journal of Refrigeration. http://www.nist.gov/customcf/get_pdf.cfm?pub_id=914052.

Policy Outlook for Low-GWP Refrigerants

The international community is negotiating an amendment to one of the most successful examples of international environmental cooperation, the Montreal Protocol, to address the global warming impact of HFCs. The Montreal Protocol phases out ODS and has achieved universal ratification by all 197 U.N. member states. As of 2014, parties to the treaty have achieved a 98% reduction in ODP[18]-weighted consumption of ODS, in part by transitioning from CFC refrigerants to either HCFC refrigerants, having much lower ODPs, or HFC refrigerants having zero ODP.[19] While the Montreal Protocol initially targeted only ODS, the international community is now considering how to use this successful framework to address the global warming impact of synthetic gases as well. To address HFCs, four separate groups (North America, the European Union, Pacific Island nations, and India) each submitted proposal amendments to the Montreal Protocol in 2015 to reduce GWP-weighted HFC production and consumption to 10-15% or less of “baseline” levels by 2050 through incremental reductions over several decades.

As was the case with the phase-down of ODS, countries often take advance action that is in many cases more aggressive than the Montreal Protocol. While these HFC amendments are under negotiation, many countries have been acting on their own to reduce use and emissions; track production, import and export; and to phase down the highest GWP HFCs. In many countries, including the US, HFC venting prohibitions have been in place for more than a decade.

Pathway to a Sustainable A/C Future

The global community can play a valuable role in driving the adoption of sustainable A/C systems. The path to this sustainable future of A/C will depend upon the international community developing a cohesive set of solutions that are interdisciplinary and collaborative. Mission Innovation, launched at the 2015 Paris Climate Conference, is an international initiative to dramatically accelerate clean energy innovation by both the public and private sectors.[20] This and similar programs, such as the Clean Energy Ministerial’s Advanced Cooling Challenge, can play an important role in meeting international climate change mitigation goals.

Figure ES-2 shows that among all key mechanisms available to reduce A/C emissions, non-vapor compression technologies can play an important role in the long-term solution since they are the only mechanism available with the potential to eliminate direct emissions while simultaneously reducing indirect emissions. In the near term, reducing direct GHG emissions through a transition to low-GWP refrigerants is a high-priority. Additionally, the continued, simultaneous pursuit of cost effective efficiency improvements is important to reduce indirect emissions. Other mechanisms can play important roles as well, such as the pursuit of cooling load reductions, waste-heat recycling, and carbon-intensity reductions in electricity generation to limit GHG emissions from A/C growth projected to occur in developing nations with hot climates.

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[18] Ozone depletion potential. Refers to the amount of stratospheric ozone degradation a chemical compound can cause relative to the same mass of R-11, a CFC.

[19] UNEP. 2014. “International Standards in Refrigeration and Air-Conditioning: An Introduction to Their Role in the Context of the HCFC Phase-out in Developing Countries.” http://www.unep.fr/ozonaction/information/mmcfiles/7679-e-International_Standards_in_RAC.pdf. Includes other sectors, such as aerosols and foam blowing that have also phased down ODS consumption under the Montreal Protocol.

[20] DOE. 2015. “Announcing Mission Innovation.” http://www.energy.gov/articles/announcing-mission-innovation.

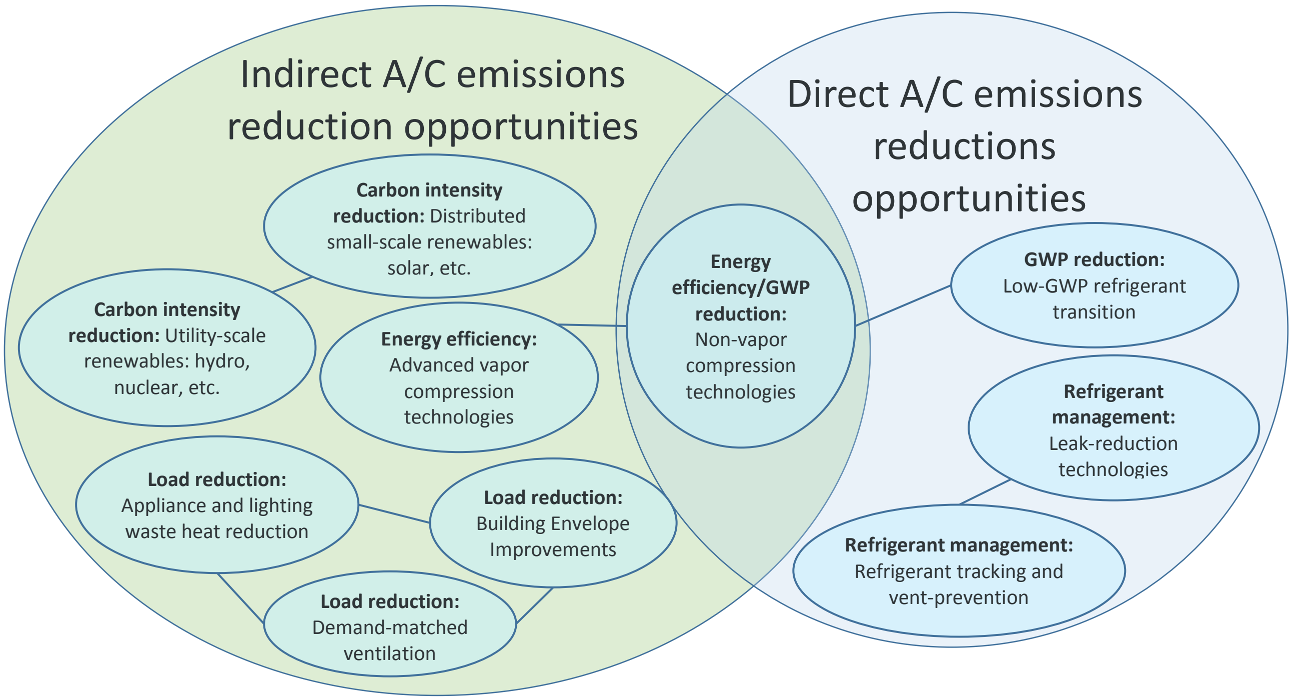

Figure ES-2: Elements of sustainable, low-emissions A/C systems

Table ES-3 highlights the initiatives that stakeholders could include in a comprehensive approach to meet global goals.

Table ES-3: Key Initiatives for a Sustainable A/C Future

Key Initiative	Specific Activities
International Collaboration	• Increase HVAC research and development, with emphasis on high-ambient-temperature countries, such as through Mission Innovation • Increase HVAC deployment activities, such as the Advanced Cooling Challenge Campaign through the Clean Energy Ministerial, again with emphasis on high-ambient-temperature countries
Domestic Policy and Regulation	• Implement domestic regulations aimed at phasing down HFC consumption • Develop robust refrigerant management schemes to mitigate emissions of existing high-GWP refrigerant stocks • Implement and periodically strengthen minimum efficiency standards • Provide example policies, strategies, and support to allow a smooth transition to energy-efficient, low-GWP systems
Emerging Technology R&D	• Support R&D to develop, demonstrate, and deploy high efficiency A/C equipment using low-GWP and NVC technologies • Continue support for sustainable building design, renewable integration, and waste heat recycling • Collaborate with developing nations to ensure cost-effective adoption of new technologies

Ensuring the implementation of the solutions outlined in Table ES-3 to reduce A/C-related emissions requires a comprehensive strategy based on international collaboration, domestic policy action, and R&D support from private and public sources. Despite the numerous challenges, the A/C industry has successfully responded to international environmental issues through the phase-out of ODS refrigerants, and can assume a leading role in reducing global GHG emissions by leveraging past success and lessons learned.

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1 Introduction

1.1 Background

The Building Technologies Office (BTO) within the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy works with researchers and industry to develop and deploy technologies that can substantially reduce energy consumption and greenhouse gas (GHG) emissions in residential and commercial buildings. Air conditioning (A/C) systems contribute GHG emissions both directly through refrigerant leakage and indirectly through fossil fuel combustion used to generate electricity to power the systems. BTO aims to facilitate research and development (R&D) on advanced HVAC technologies that support a phasedown of refrigerants that contribute to global warming, such as hydrofluorocarbons (HFCs), while also driving down lifecycle cooling costs over time through greater energy efficiency.

A/C was once, and in many places still is, considered a luxury due to the cost of the product and the electricity required to operate it. Today, an estimated 15% of the global population has A/C, providing comfortable indoor temperatures and high indoor air quality.[21] In many regions, A/C is increasingly becoming a humanitarian necessity amidst increasing global temperatures. In India in 2015, for example, more than 2,300 people died in one of the worst heat waves ever.[22]

Rapidly growing global A/C demand in the 21st century will cause further climate damage unless governments, businesses, and other organizations take steps to reduce direct and indirect impacts from A/C usage. While adoption of A/C in developed countries increased rapidly in the 20th century, the 21st century will see greater adoption in rapidly growing developing countries, especially those in hot and possibly humid climates with large and growing populations, such as India, China, Brazil, and Middle Eastern nations. Increasing gross domestic product (GDP) in these nations opens the door to A/C for millions of people who may now be able to afford a system. By 2050, the A/C demand in non-OECD countries will increase global A/C energy consumption by 2.5 times 2010 levels under a business-as-usual scenario.[4]

The *Montreal Protocol on Substances that Deplete the Ozone Layer* (i.e., The Montreal Protocol) phases out ozone-depleting substances (ODS), such as chlorofluorocarbons (CFC, e.g., R-12) and hydrochlorofluorocarbon (HCFC, e.g., R-22) refrigerants, and is one of the most successful examples of international cooperation to address environmental impacts. Initially adopted in 1987, it became the first international treaty to achieve universal ratification by all 197 U.N. member states in 2009. As of 2014, parties to the Montreal Protocol have phased out 98% of ODP-weighted consumption of ODS,[23] in part by transitioning from CFC refrigerants to either

[21] A/C penetration percentage estimate of 15% based on regional penetration projections for 2015 by McNeil and Letschert (2008) and national population estimates for 2015 from CIA World Factbook.
McNeil, Michael, and Virginie Letschert. 2008. "Future Air Conditioning Energy Consumption in Developing Countries and What Can Be Done about It: The Potential of Efficiency in the Residential Sector." Lawrence Berkeley National Laboratory. Available at: http://escholarship.org/uc/item/64f9r6wr;
CIA World Factbook. Accessed April 2016. Available at: https://www.cia.gov/library/publications/resources/the-world-factbook/

[22] Inani, Rohit. 2015. "More Than 2,300 People Have Now Died in India's Heat Wave." Time Magazine, June 2. http://time.com/3904590/india-heatwave-monsoon-delayed-weather-climate-change/.

[23] Includes other sectors, such as aerosols and foam blowing that have also phased down ODS consumption

HCFC refrigerants, having much lower ODPs, or HFC refrigerants having zero ODP.[19] Article 5 countries, those developing countries that met ODS consumption limits at the time of adoption, have a longer timeframe than non-Article 5 countries to phase out their use of HCFCs. With this longer phase-out timeline, HCFCs are still in widespread use for A/C in Article 5 countries.[24]

The A/C industry has a long history of meeting national and global goals through international cooperation and technology innovation. Manufacturers successfully transitioned from ODS under the Montreal Protocol, and continually innovate to deliver products with higher efficiency and performance at lower costs. HFC refrigerants (e.g., R-410A, R-407C, and R-134a) are replacing HCFC and CFC refrigerants and now dominate the industry in developed countries. However, HFC refrigerants have high global warming potential (GWP). In a proposed amendment to the Montreal Protocol, the United States, Mexico and Canada target GWP-weighted HFC consumption reductions of 85% during the period of 2019–2046.[25] While international negotiations continue, the A/C industry continues to innovate on the next generation of refrigerants with lower GWPs to reduce direct environmental impacts while also improving A/C system efficiency to reduce indirect impacts.

Most A/C systems operate using a vapor-compression cycle containing a refrigerant as a working fluid – an architecture that has not changed fundamentally in nearly 100 years. However, the GWP of today's common refrigerants are 1,000s of times that of the most prevalent anthropogenic GHG, carbon dioxide. This report collectively classifies alternative refrigerants as "low GWP" if they have a lower GWP than common HFC refrigerants for a specific application, which are classified as "high GWP".

New technologies show promise to reduce direct climate impact through the reduction or elimination of refrigerants altogether and to reduce indirect climate impact through increased energy efficiency. The market-readiness of these technologies varies, ranging from detailed conceptual evaluation to commercial availability. Each of these technologies gives a glimpse at what the future may hold for the A/C industry and the global A/C market.

1.2 Report Objective

This report highlights current trends in the global A/C market related to both direct and indirect climate impacts and then discusses the projected future global warming impacts from increased global A/C usage. The report documents future impacts and the technology options that may help achieve global goals, including pathways related to low-GWP refrigerants, energy efficiency improvements, R&D initiatives, and regulatory actions.

With this report, DOE provides a vision for the future of the industry by building on a variety of available resources, including many widely accepted projections and knowledge of A/C R&D progress. DOE intends for this vision to reflect a broad aggregation of perspectives, including potentially opposing positions that international stakeholders are seeking to overcome in order to achieve global goals. DOE brings together this content in an effort to support dialogue in the international community and help maintain key facts at the forefront of discussions.

[24] A full list of Article 5 and non-Article 5 countries is available at: http://ozone.unep.org/en/article-5-parties-status
[25] UNEP. 2013. Proposed Amendment to the Montreal Protocol Submitted by Canada, Mexico and the United States of America. http://conf.montreal-protocol.org/meeting/oewg/oewg-33/presession/PreSession%20Documents/OEWG-33-3E.pdf.

1.3 Technology and Market Scope

This report focuses on A/C and reversible heat pump systems for use in stationary building applications, including the following applications:

- Residential equipment
  - Packaged room A/C and portable A/C
  - Ducted split and single-package AC
  - Ductless split system A/C
- Commercial equipment
  - Packaged Rooftop Unit A/C
  - Commercial Ductless A/C
  - Chillers
  - Packaged Terminal A/C
  - Computer Room A/C

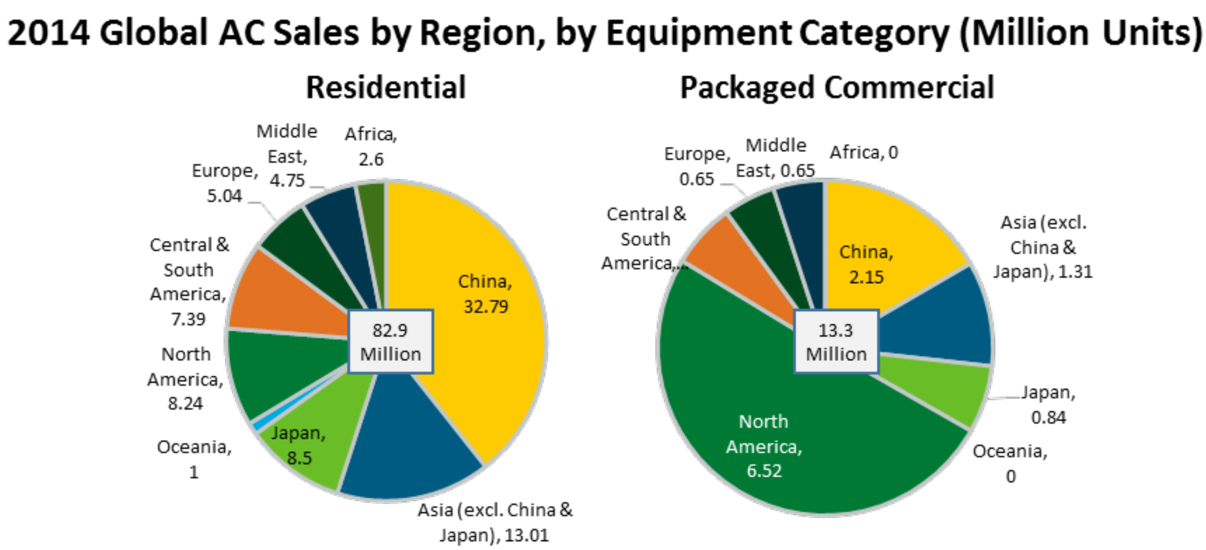
While many of the same technologies, and trends may apply to mobile A/C, heating-only heat pumps (for cold climates), and refrigeration, we do not address such equipment within this report.

2 Current and Projected Air Conditioning Usage

A/C systems became a common feature of residential and commercial buildings in much of the developed world during the 20th century, bringing about significant benefits to human health, productivity and comfort. With rising global temperatures and increasing GDP in developing nations, the expected demand for A/C in developing countries in the coming decades will greatly increase the associated global GHG emissions as these nations seek to achieve the same health, productivity and comfort benefits often taken for granted by more developed nations. Although most A/C systems use the same underlying vapor-compression refrigeration cycle, different markets have adopted different system architectures and refrigerants, making the global equipment landscape very diverse.

2.1 Current and Projected Global Markets for Air Conditioning

Air conditioning equipment represents close to a $100 billion, 100 million-unit global market annually, which includes replacement of existing equipment, equipment for new buildings, as well as equipment for buildings previously without air conditioning. Figure 2-1 shows these data, including residential and packaged commercial equipment, but does not include commercial chillers, which account for an additional 400,000 units and $8.5 billion annually.[26]



Source: eJARN 2015 citing BSRIA market research[27]

Figure 2-1: Global A/C sales by region, by equipment category (million units)

The comfort and health benefits of A/C can be at odds with the goals of conserving energy and reducing the emissions that contribute to global climate change. Residential and commercial

[26] Milnes, Julian. 2014. "Global A/C Market Starting to Warm Up." ACHR News. August 18, 2014. Citing BSRIA data. Available at: http://www.achrnews.com/articles/127385-global-ac-market-starting-to-warm-up
[27] JARN. 2015. "BSRIA World Air Conditioning Market Study." May 30, 2015. Available at: http://www.ejarn.com/news.aspx?ID=34847

buildings together account for approximately one-third of global end-use energy consumption[28] with A/C contributing 4% of building site energy consumption globally.[29] In the past decade, A/C efficiency has improved (see Section 5.1), but these improvements have only partially offset the increased demand. In this time, global space cooling-related energy demand has increased 43%, exceeding the growth in both population (13%) and building floor space (34%).[30]

While some limited growth in A/C demand in developed nations is expected, rising standards of living and population growth in developing nations will be the primary drivers of global A/C demand growth. The A/C market in developed nations is relatively mature; as an example, nearly 90% of homes in the U.S. have central or room air conditioners.[31] The International Energy Agency (IEA) projects that A/C energy consumption by 2050 will increase 4.5 times over 2010 levels for non-OECD countries versus 1.3 times for OECD countries (See Figure 2-2). Rising global temperatures resulting from climate change will also contribute to increased A/C demand, creating the unfortunate potential for a feedback loop in which increased emissions from electricity generation to meet this demand, as well as refrigerant leakage, drives higher average global temperatures. Under a scenario of 3.7°C average temperature increase from pre-industrial times, cooling demand may increase by 70% or more above the projections in Figure 2-2.[32]

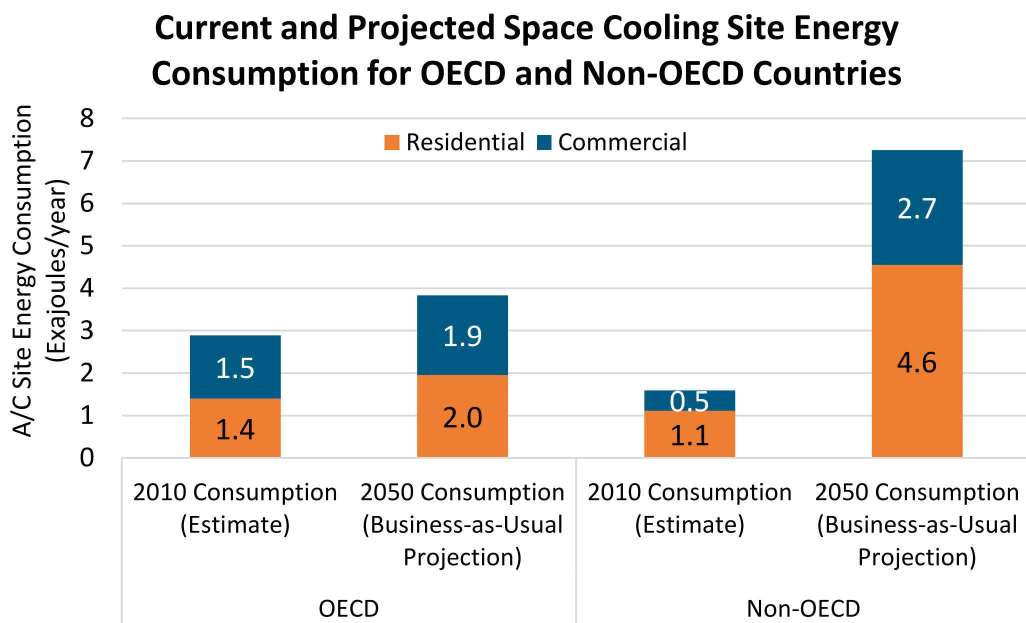
[28] IEA. 2011. "Technology Roadmap: Energy-Efficient Buildings: Heating and Cooling Equipment." Paris: International Energy Agency. https://www.iea.org/publications/freepublications/publication/buildings_roadmap.pdf.

[29] IEA. 2013. "Transition to Sustainable Buildings: Strategies and Opportunities to 2050." Paris: International Energy Agency. http://www.iea.org/publications/freepublications/publication/transition-to-sustainable-buildings.html

[30] IEA. 2015. "Energy Efficiency Market Report 2015: Market Trends and Medium-Term Prospects." Paris: International Energy Agency. https://www.iea.org/publications/freepublications/publication/MediumTermEnergyefficiencyMarketReport2015.pdf.

[31] EIA. 2011. "Residential Energy Consumption Survey." U.S. Energy Information Administration. https://www.eia.gov/consumption/residential/reports/2009/air-conditioning.cfm.

[32] IPCC. 2014. "Climate Change 2014: Mitigation of Climate Change." Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change." Intergovernmental Panel on Climate Change. https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_full.pdf.

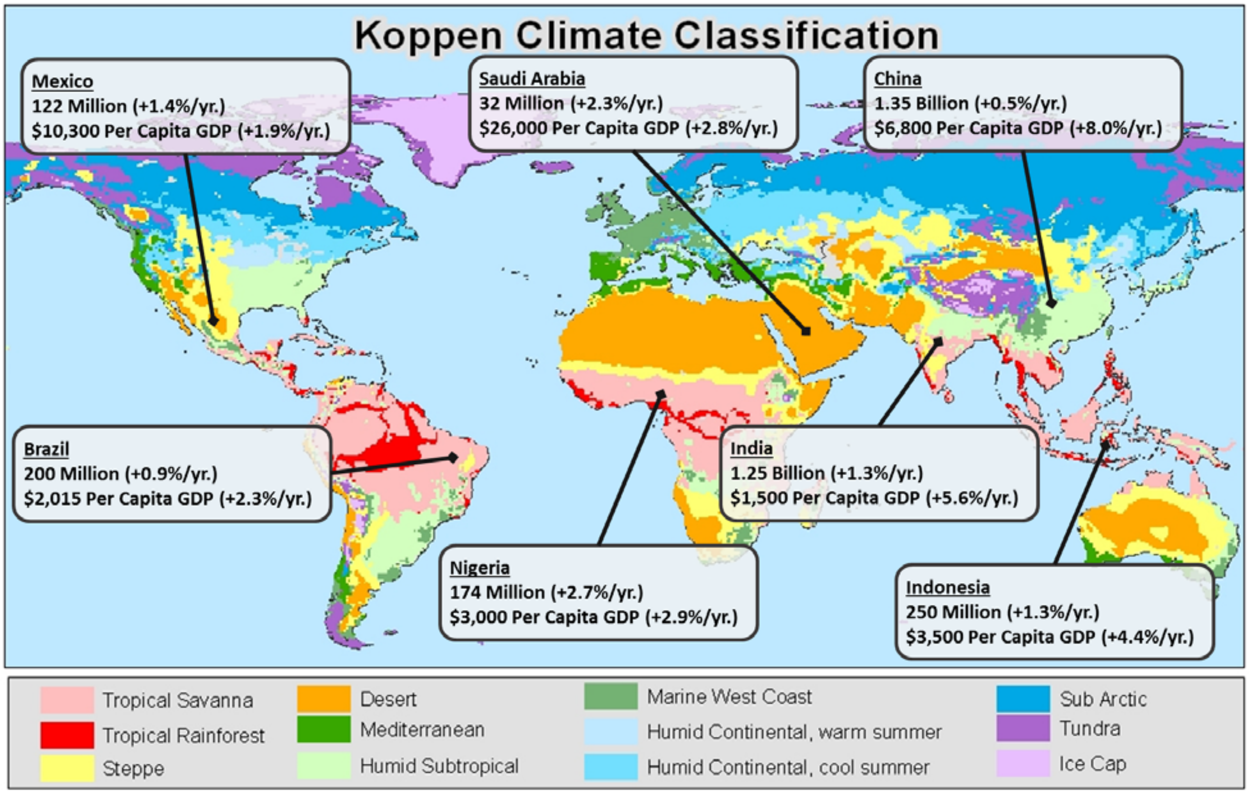


Source: IEA (2013)[4] (Exajoule [EJ] = 10^{18} Joules or 0.95 Quadrillion [10^{15}] Btus)

Figure 2-2: Current and projected space cooling site energy consumption[33]

Many developing countries not only have large populations, but also have warmer climates than developed countries, further increasing potential A/C demand and associated energy consumption relative to developed countries. Figure 2-3 shows data on some of the countries where hot climate coincides with rapidly growing populations and prosperity.

[33] Note – source or primary energy consumption is approximately 3x site electricity consumption globally. International Energy Agency. 2013. "Transition to Sustainable Buildings: Strategies and Opportunities to 2050." Figure 1.5. OECD/IEA. Available at: https://www.iea.org/media/training/presentations/etw2014/publications/Sustainable_Buildings_2013.pdf



Source: CGIAR,[34] United Nations,[35] World Bank[36]

Figure 2-3: Global climate map showing growth in population and per capita GDP (2014)

With the backdrop of rising global temperatures and improving living standards, market penetration for A/C systems is expected to grow substantially from current levels in developing nations. For example, residential A/C saturation in India was estimated at only 3% in 2010, compared to over 90% in the U.S. [31,37] Table 2-1 projects the potential space cooling demand for 11 developing countries relative to the U.S., based on population and cooling degree-days.[38] The "Relative Cooling Demand Potential" represents the relative cooling demand each country could expect if that country were to use space-cooling equipment at a rate comparable to the U.S. For example, India alone has potential space cooling demand that is 14 times, or 1,400%, larger than the U.S. Since cooling degree-days do not account for humidity, the actual potential demand may vary from these estimates. Given that many of these countries are in humid, tropical climates, these data represent conservative estimates.

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[34] CGIAR. Available: http://gisweb.ciat.cgiar.org/metadata/atlasbiofort/koppenclimateclass.htm Accessed June 2016.

[35] United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision. Accessed April 2016. Available at: http://esa.un.org/unpd/wpp/DataQuery/. (Population growth rates are average 2010-2015).

[36] World Bank data for 2014. Accessed April 2016. Available at: http://data.worldbank.org/. (GDP growth rates are average 2010-2014).

[37] Phadke, Amol. 2014. "Avoiding 100 New Power Plants by Increasing Efficiency of Room Air Conditioners in India: Opportunities and Challenges." Lawrence Berkeley National Laboratory. July 16, 2014. Available at: http://escholarship.org/uc/item/5h9593bc#page-2

[38] Cooling degree-days (CDD) are a relative measure of space cooling demand based on the difference between the outside ambient temperature and a reference temperature corresponding to a comfortable indoor temperature.

Table 2-1: Cooling Demand Potential in Developing Countries

Country	Population (millions)	Annual Cooling Degree Days (CDDs) [a]	Annual GDP per Capita ($1,000)	Total Cooling Demand Potential (Billion Person CDDs)[b]	Relative Cooling Demand Potential (Normalized to the U.S)[a]
USA	**316**	**882**	**53.0**	**279**	**100%**
India	1,252	3,120	1.5	3,906	1,400%
China	1,357	1,046	6.8	1,419	510%
Indonesia	250	3,545	3.5	886	320%
Nigeria	174	3,111	3.0	541	190%
Pakistan	182	2,810	1.3	511	180%
Brazil	200	2,015	11.2	403	140%
Philippines	98	3,508	2.8	344	120%
Mexico	122	1,560	10.3	190	70%
Egypt	88	1,836	11.5	162	60%

a: CDDs in the table use a reference temperature of 18°C and the annual CDDs for different regions of each country, weighted by the geographical distribution of the population.
B: Denotes the product of population and CDD per year and may be used to approximate space cooling energy demand relative to that of the U.S. if developing countries were to adopt comparable air conditioning use patterns.
Source for all countries except Egypt: Davis and Gertler (2015)[39] citing Sivak M (2013)[40]
Source for Egypt: CIA World Factbook[41], Climate Analysis Indicators Tool (CAIT): World Resources Institute[42]

2.2 Baseline Equipment and Refrigerant Types by Application

The vast majority of air conditioners around the world today operate using a vapor-compression refrigeration cycle.[43] However, designs and configurations differ around the world to meet different market needs. For example, ductless split systems from mostly Asian manufacturers are commonplace for residential and commercial applications nearly everywhere except for the U.S. Ducted systems and room air conditioners dominate the U.S. residential market due to different construction conventions. Appendix A: System Descriptions provides more detailed descriptions and images for each equipment type as well as information on efficiencies and capacities.

[39] Davis, Lucas, and Paul Gertler. 2015. "Contribution of Air Conditioning Adoption to Future Energy Use under Global Warming." Proceedings of the National Academy of Sciences of the United States of America 112 (119). Available at http://www.pnas.org/content/112/19/5962.full.
[40] Sivak, Michael. 2013. "Will AC Put a Chill on the Global Energy Supply?" American Scientist. Available at: http://www.americanscientist.org/issues/pub/will-ac-put-a-chill-on-the-global-energy-supply.
[41] CIA World Factbook. Accessed April 2016. Available at: https://www.cia.gov/library/publications/resources/the-world-factbook/
[42] ChartsBin Worldwide Cooling Needs. Accessed April 2016. Available at: http://chartsbin.com/view/1030 citing cait.wri.org
[43] UNEP. 2014. "2014 Report of the Refrigeration, Air Conditioning, and Heat Pumps Technical Options Committee." Kenya: United Nations Environmental Programme. Available at: http://ozone.unep.org/sites/ozone/files/documents/RTOC-Assessment-Report-2014.pdf. We assume that absorption and other non-vapor compression systems constitute less than 1% of the current installed base of systems.

Residential A/C systems generally range in capacity from 1.75-18 kW_{th} (0.5 to 5 refrigeration tons[44]) and can be centralized to serve the entire home, or distributed to serve individual rooms. Some larger residential buildings (e.g., high-rise multi-family buildings) may use commercial equipment. Individual room (i.e., window, mini-split and portable) systems are common throughout most of the world. The North American market commonly uses central ducted A/C for whole home cooling. While mini-split (i.e., ductless) hold a small but growing share of the North American market, they are the predominant system type throughout most other markets.

Commercial A/C systems generally range in capacity from 18-7,020 kW_{th} (5 to 2,000 tons) or more. Equipment may be centralized for the entire building or distributed for individual building zones. Smaller or low-rise commercial buildings (light-commercial applications) commonly use air as the thermal distribution medium, whereas larger buildings more commonly use chilled water (i.e., hydronic) distribution systems. Small commercial buildings, especially those not originally designed for A/C, may use residential-size equipment. The commercial market is very diverse, covering a much larger capacity range and variety of architectures than exhibited in the residential market.

Table 2-2 summarizes the most common refrigerants currently used in new and existing equipment in Article 5 and Non-Article 5 countries.[45] Section 0 discusses history of refrigerant adoption, the role of the Montreal Protocol in global refrigerant usage, and international efforts to develop more environmentally friendly refrigerants.

Table 2-2: Common Refrigerants for New and Existing Equipment

Country Classification	Category	Refrigerants for Existing Equipment	Refrigerants for New Equipment
Non-Article 5 Countries	Packaged & Split-Systems	Typical – post 2000: R-410A Typical – older: R-22 Others: R-407C, R-134a, R-290, R-32	Typical: R-410A Others: R-407C, R-134a, R-290, R-32
	Chillers	Typical – post 2000: R-134a, R-410A Typical – older: R-22 Others: R-123	Typical: R-134a, R-410A Others: R-290, R-744, R-1234yf, R-1234z(e), R-1233zd(e), R-514A, others
Article 5 Countries (delayed ODS phasedown)	Packaged & Split-Systems	Typical: R-22 Others: n/a	Typical: R-22 Others: R-407C, R-410A, R-290, R-32
	Chillers	Typical: R-22, R-11, R-12, R-123 Others: R-134a, R-410A, R-290, R-744	Typical: R-22, R-134a, R-410A Others: R-123, R-290, R-744

Source: UNEP (2014)[43]

[44] Refrigeration tons is the nominal cooling capacity of the equipment, where 1 ton = 12,000 Btu/hr. = 3.52 kW_{th}.

[45] The Montreal Protocol separates phase-down requirements and timelines for developing (Article 5) and developed (non-Article 5) countries. Accessed April 2016. Available at: http://ozone.unep.org/en/handbook-montreal-protocol-substances-deplete-ozone-layer/22.

3 Global Warming Contributions

A/C systems contribute to GHG emissions via two distinct pathways. Electricity consumption throughout the useful life of A/C systems is the largest driver of GHG emissions from A/C. Direct refrigerant emissions (e.g., leaks), despite having a lower overall contribution, offer an important path to significantly reducing A/C GHG emissions in addition to efficiency improvements. Key elements to achieving near-term reductions in climate impacts for A/C include replacing the current generation of HFC refrigerants with low-GWP refrigerants through phasedown under the Montreal Protocol and/or domestic regulations concerning their use; and reducing emissions during initial charging, servicing, and end-of-life disposal. This section presents global annual and individual life cycle climate impacts of A/C systems, taking into account both energy efficiency and refrigerant emissions, to assist policymakers in evaluating phasedown approaches.

3.1 Direct and Indirect Global Warming Contributions

A/C systems contribute to global warming through both direct and indirect GHG emissions:

- **Direct emissions** occur when refrigerant escapes from the A/C system into the atmosphere during initial charging, servicing, end-of-life disposal, and other events
- **Indirect emissions** result from fossil fuel combustion to generate electricity to operate the A/C system

Emissions of HCFC and HFC refrigerants have a disproportionately large global warming impact relative to their mass, as many refrigerants have GWPs several thousand times higher than that of carbon dioxide. Table 3-1 summarizes the environmental properties of various A/C refrigerants, reporting the ozone depletion potential (ODP) and GWP of each, as well as the estimated annual amount of each gas type produced globally, for all applications. Note that CFCs have been phased out internationally and HCFCs are currently undergoing a similar phase-out per the Montreal Protocol (See Section 8).

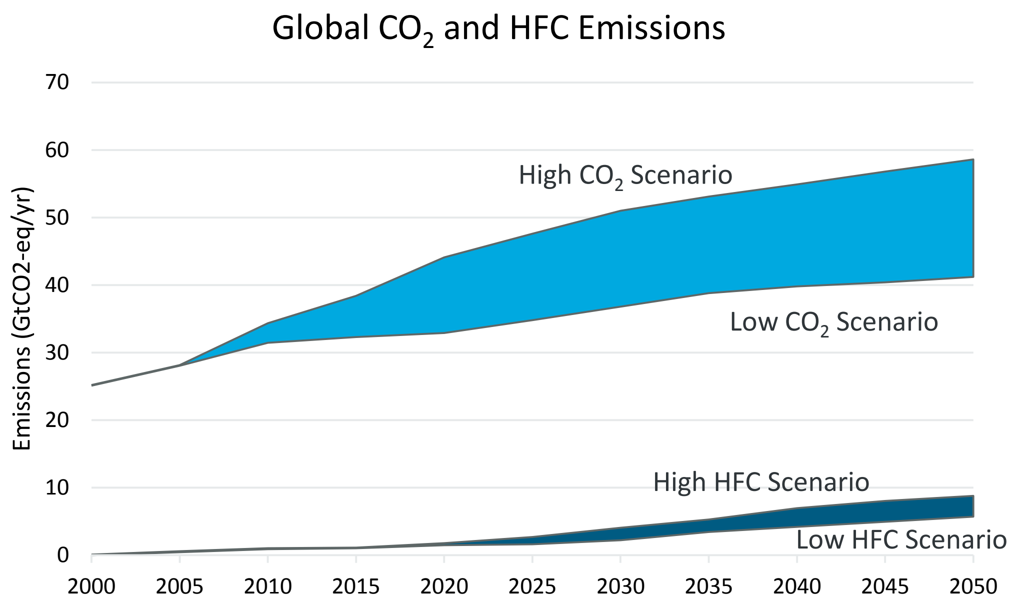
Table 3-1: Environmental Impact and Production for Common A/C Refrigerants

Refrigerant	F-gas Category	Ozone Depletion Potential (ODP)[a]	100 year GWP[a]	2010 Global Production (kilotons)[b]
R-11	CFC	1.0	4,660	0
R-12	CFC	0.73	10,200	
R-22	HCFC	0.034	1,760	600
R-123	HCFC	0.01	79	
R-134a	HFC	0.0	1,300	400
R-410A	HFC	0.0	1,924	
R-407C	HFC	0.0	1,624	
R-32	HFC	0.0	677	
R-290	Non-Fluorinated	0.0	3	n/a[c]
R-744	Non-Fluorinated	0.0	1	

a) IPCC (2013)[46] GWP values of R-410A and R-407C calculated by mass-weighting the component GWPs.
b) UNEP (2011).[47] Figure ES-1. CFCs are still produced in very small amounts for atmospheric chemistry and other research. Emissions of CFCs are non-zero due to legacy emissions from older systems.
c) Data on the production of these substances specifically for use as refrigerants is not available.

HFCs and HCFCs are members of a family of high-GWP fluorinated gases (F-gases) that also includes perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3), all of which have no natural sources and result only from human activities.[48] Excluding HCFCs, fluorinated gases accounted for approximately two percent of total GHG emissions,[32] (from all sources) in 2010 and are increasing rapidly. The Intergovernmental Panel on Climate Change (IPCC) expects these emissions, if not addressed, to continue to grow rapidly in the coming decades, largely due to increased HFC consumption to meet rising cooling demand.[32] Substitution for ozone-depleting HCFCs will also contribute to HFC demand growth.[47] Under a business-as-usual scenario, global HFC emissions for all applications could be equivalent to 9-19% of projected global CO_2 emissions by 2050 (see Figure 3-1).[49]

[46] IPCC. 2013. "Climate Change 2013 The Physical Science Basis" Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available at: http://www.climatechange2013.org/images/report/WG1AR5_Chapter08_FINAL.pdf
[47] UNEP. 2011. "HFCs: A Critical Link in Protecting Climate and the Ozone Layer." United Nations Environmental Programme. Available at: http://www.unep.org/dewa/Portals/67/pdf/HFC_report.pdf.
[48] EPA. 2015. "Emissions of Fluorinated Gasses." United States Environmental Protection Agency. Available at: https://www3.epa.gov/climatechange/ghgemissions/gases/fgases.html. Accessed April 2016
[49] Velders, et al. 2009. "The Large Contribution of Projected HFC Emissions to Future Climate Forcing." Proceedings of the National Academy of Sciences of the United States of America 106 (27): 10949–54. Available at: http://www.pnas.org/content/106/27/10949.full



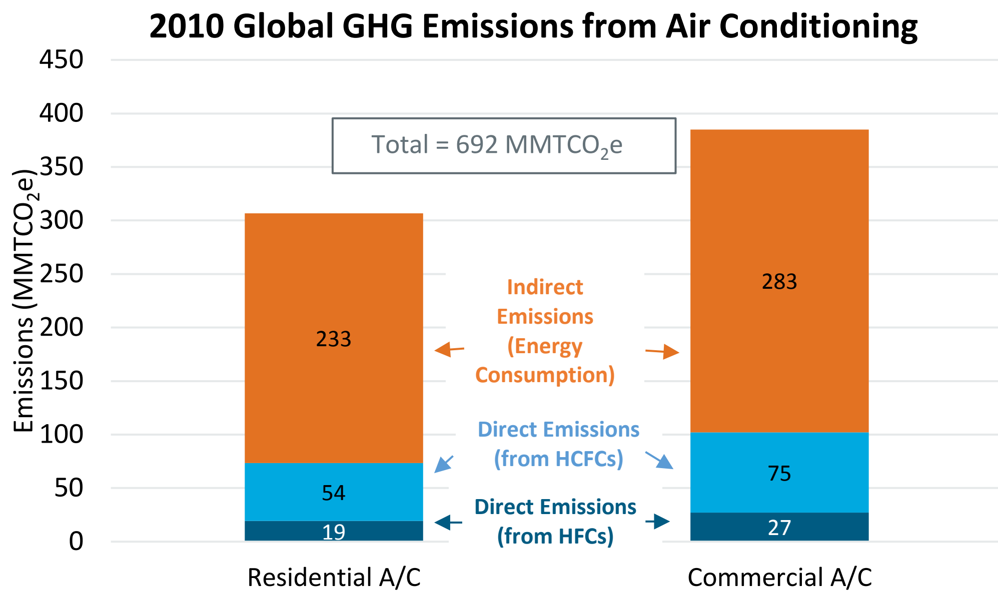
Source: Adapted from Velders et al. (2009)[50]

Figure 3-1: Global CO_2 and HFC Emissions Projections

Despite the high GWPs of most refrigerants in use today, indirect emissions from electricity generation are responsible for the majority of A/C GHG emissions. An analysis of available data sources[51] found indirect emissions from electricity generation account for approximately 74% of annual CO_2-equivalent emissions from A/C systems (including chillers), with direct emissions of HFCs and HCFC refrigerants accounting for 7% and 19% of annual global CO_2-equivalent emissions from A/C, respectively. Estimations of direct and indirect impacts are subject to significant uncertainty and depend heavily upon assumptions regarding operating and end-of-life refrigerant leakage rates, climate, system type, and electricity generation mix. Figure 3-2 summarizes annual global direct and indirect CO_2-equivalent emissions for residential and commercial A/C systems in 2010. Appendix B provides the methodology and assumptions used in developing these estimates.

[50] Velders, et al. 2009. "The Large Contribution of Projected HFC Emissions to Future Climate Forcing." Figure 2B. Proceedings of the National Academy of Sciences of the United States of America 106 (27): 10949–54. Available at: http://www.pnas.org/content/106/27/10949.full CO_2 emissions projections are sourced from the IPCC's 2000 Special Report on Emissions Scenarios (SRES) and are based upon GDP and population growth scenarios. HFC emissions projections (from all sources) follow from the same underlying SRES scenarios for GDP and population growth. Both emissions projection ranges assume existing policies.

[51] This analysis relies upon energy consumption and emissions data from the U.N.'s Intergovernmental Panel on Climate Change, U.S. EPA, World Bank, and the Proceedings of the U.S. National Academy of Sciences.



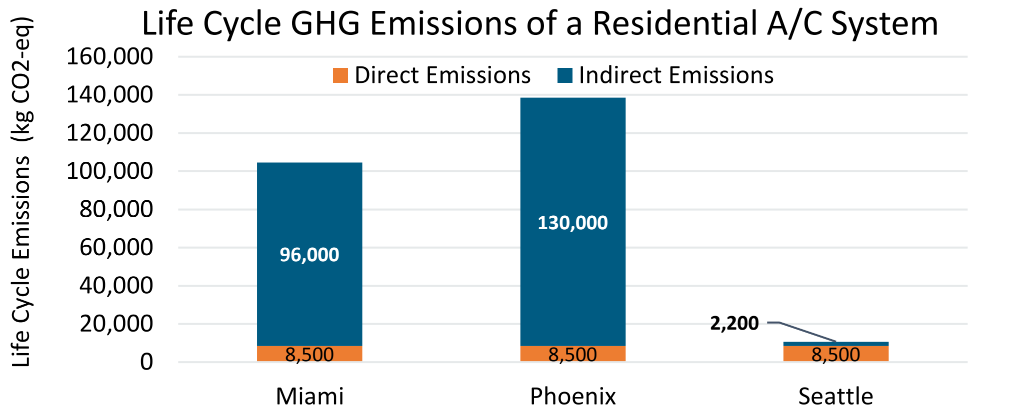
Sources: IPCC (2014),[32] World Bank (2014),[209] EPA (2012),[210] Xiang, et al. (2014),[211] ICF (2007)[212]

Figure 3-2: Estimated global GHG emissions from A/C systems in 2010

The relative contributions of direct and indirect emissions of individual cooling systems may vary widely from the global averages reported in Figure 3-2, above. For example, refrigerant emissions account for a much smaller proportion of GHG emissions from chillers than for other A/C systems due to very low leakage rates relative to their space cooling production.[43] Additionally, indirect emissions from energy consumption will account for a higher proportion of life cycle GHG emissions for a unit installed in a location with a warm climate and mostly coal-fired electric generation, than for a unit installed in a cooler climate with more renewable generation. The relative contribution of direct emissions for individual units may also be higher or lower than the global averages reported, depending on refrigerant leakage rates, charge sizes, and repair and recovery practices.

Figure 3-3 reports examples of life cycle GHG emissions of individual residential unitary A/C systems installed in:

- **Miami, Florida, U.S.** – a hot, humid, coastal city in the southern U.S. with a generation mix relying primarily on natural gas.
- **Phoenix, Arizona, U.S.** – a hot, dry, inland city in the southwestern U.S. with a generation mix relying primarily on natural gas and coal.
- **Seattle, Washington, U.S.** – a temperate marine city in the northwestern U.S. with a large proportion of hydroelectric and other renewable generation



	Miami	Phoenix	Seattle
Generation Carbon Intensity (kg CO_2 / kWh)	0.51	0.52	0.3
Cooling Degree Days (15.5 ^oC Base Temp)	3,590	3,670	445

Source: ORNL/UMD LCCP Tool,[52] EPA Power Profiler[53], Degreedays.net[54]

Figure 3-3: Life cycle GHG emissions of residential air-conditioning systems[55]

Direct emissions in Article-5 countries are likely much higher than shown in Figure 3-3, as few of these nations have been successful in implementing in-service recovery practices or end-of-life refrigerant recycling programs, which often leads to deliberate venting of refrigerants.[56] Venting at the end of product life (i.e., a 100% end-of life refrigerant loss) would nearly double life cycle refrigerant emissions (i.e., to over 16,500 kg-CO_2-equivalent for all cases shown in Figure 3-3). Less conservative assumptions for leakage rates during operation and servicing would also increase direct emissions estimates. While the average carbon intensity of electricity generation in the U.S is slightly higher than the global average, developing nations tend to rely more heavily on coal than the U.S. As an example, the emissions factor for India is over 900 g CO_2/kWh, and over 700 g CO_2/kWh for China, compared to approximately 515 g CO_2/kWh for the U.S.[209] Indirect emissions are therefore likely to be correspondingly higher in these nations.

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[52] Oak Ridge National Laboratory and University of Maryland. 2013. Life Cycle Climate Performance - Residential Heat Pump. Accessed April 2016. Available at: http://lccp.umd.edu/ornllccp/ASHPSystemInputs.aspx. Assumes cooling-only operation.
[53] EPA. 2015. Power Profiler. Accessed April 2016. Available at: https://oaspub.epa.gov/powpro/ept_pack.charts.
[54] Bizee Software, and Weather Underground. n.d. "Degree Days.net." Accessed April 2016. Available at: http://www.degreedays.net/. 5 year annual average CDDs at each city's major airport.
[55] Boxed values denote the carbon intensity of each city's generation mix, according to EPA's Power Profiler tool. U.S. average emissions factor = 0.515 kg/kWh; slightly higher than the global emissions factor (0.48 kg/kWh) used in Figure 3-2. Electrical generation in Miami and Phoenix have similar carbon intensities because Miami's lower nuclear generation capacity offsets emissions reductions of using more natural gas and less coal. Note that each of the emissions factors reported are regional rather than global averages, and will necessarily vary from the value used in the global calculations reported in Figure 3-2. Estimates of direct emissions for each city assume a constant 10 lb. (4.54 kg) R-410A charge with 0% leakage during servicing, 5% annual leakage during operation, 15% end-of-life refrigerant loss, and 15-year operating life.
[56] UNEP. 2010. "Alternatives to HCFCs in the Refrigeration and Air Conditioning Sector." United Nations Environmental Programme. Available at: http://www.unep.org/pdf/hcfc-alternatives__.pdf.

3.2 Climate Impacts of Low-GWP Refrigerant Transition

Transitioning to low-GWP refrigerants could eliminate the majority of direct emissions and therefore significantly reduce A/C GHG contributions, especially for Article 5 countries. While electricity consumption is the largest driver of GHG emissions from A/C (i.e., indirect impacts), the high global warming impact of today's refrigerants means that a global transition to low-GWP alternatives could significantly reduce CO_2-equivalent emissions from A/C systems as quickly as a single turnover cycle of installed equipment. A theoretical 100% adoption of near-zero GWP refrigerants would reduce total global A/C emissions by up to 26%, assuming no changes in efficiency (see Figure 3-2). With many available low-GWP alternative refrigerants having GWPs of 100 or less (see Section 4), the industry has the opportunity to implement solutions for all applications, making total A/C GHG emissions reductions of 20% or more a realistic prospect. Addressing direct emissions therefore offers an important path to substantially reducing A/C GHG emissions.

Prompt deployment of low-GWP refrigerants offers the added benefit of mitigating direct emissions growth in countries with growing A/C markets, but lacking strong refrigerant management programs. IEA projections indicate substantial A/C market growth by 2050, especially in developing countries (see Figure 2-2). Many of these nations currently lack the programs and incentives to prevent end-of-life venting and other poor refrigerant management practices. A low-GWP transition would mitigate the growth of direct emissions as cooling demand increases.

Improving system efficiency while reducing the GWP of refrigerants is crucial for maximizing GHG reductions. Policymakers recognize this combined approach. Regulatory programs in several countries (e.g., U.S. EPA's Significant New Alternatives Policy [SNAP] program and the EU's F-gas regulations) have recently focused on prohibiting the use of higher-GWP HFCs for certain applications as elements of broader national and international climate policies (see Section 8). Policymakers are considering the life cycle climate impacts of alternative refrigerants to achieve benefits from both the replacement of current refrigerants (reducing direct emissions) and the increase in system efficiency (reducing indirect emissions). Fortunately, many low-GWP refrigerants offer comparable or better efficiencies to their higher-GWP counterparts in use today[57] (see Section 4) and will likely improve further as manufacturers optimize A/C systems for these new refrigerants.

[57] Abdelaziz, et al. 2015. "Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Mini-Split Air Conditioners" (Oak Ridge National Laboratory, 2015). Available at: http://energy.gov/sites/prod/files/2015/10/f27/bto_pub59157_101515.pdf.

4 Low-GWP Refrigerants

Refrigerant selection for A/C systems has evolved through several transitions to improve the safety, performance, and environmental impact of refrigerants. The future of low-GWP refrigerants presents surmountable challenges for an industry that has successfully navigated refrigerant transitions in the past. Research efforts are currently underway to investigate a wide range of potential alternative refrigerants for A/C systems with the goal of identifying low-GWP refrigerants with the most attractive performance and risk characteristics. AHRI's Low-GWP Alternative Refrigerant Evaluation Program[58] (Low-GWP AREP) and other testing has revealed that several low-GWP refrigerants can meet or exceed the efficiency and capacity of today's refrigerants, even in very hot and humid environments. Low-GWP refrigerants are already commercially available in many applications and markets (see Table 4-7), and with proper support, industry could deploy them globally into the next generation of equipment.

In the near-term, "drop-in" replacements for specific A/C applications can provide significant GWP reductions over today's refrigerants (e.g., 50-75%), while minimizing challenges for early adopters. These near-term replacements may include refrigerant blends (e.g., HFC / HFO blends) that will likely be less expensive than pure HFO refrigerants, because the HFC components are mature and less expensive than HFOs.

4.1 Historical Refrigerant Selection

As illustrated in Table 4-1, the A/C industry has evolved through four generations of refrigerants. The first generation included "whatever worked" – non-fluorinated substances such as hydrocarbons (HCs), ammonia (NH_3), and carbon dioxide (CO_2). Manufacturers adopted the second generation, CFCs and HCFCs, because they were efficient, non-flammable, and non-toxic. R-22, an HCFC, is the predominant second-generation refrigerant for A/C. Table 4-2 summarizes the environmental properties of different refrigerants.

In the 1970s and 1980s, scientists discovered that CFCs and HCFCs contributed significantly to the depletion of stratospheric ozone. The international effort to phase out ozone depleting, second-generation refrigerants in the 1980s culminated in the adoption of the Montreal Protocol. The parties to the Montreal Protocol have committed to phasing out CFC and HCFC consumption and production by 2040 (See Section 8). However, R-22 is still commonplace in Article 5 countries. Many non-Article 5 countries have already transitioned to third-generation HFC refrigerants (e.g., R-410A, R-134a) that are non-ozone depleting, but have high GWPs similar to CFCs and HCFCs.

[58] AHRI. 2016. "AHRI Low-GWP Alternative Refrigerants Evaluation Program." http://www.ahrinet.org/arep.aspx.

Table 4-1: Refrigerant Changes Over Time

Refrigerant Category	Timeline	Example Refrigerants
1st Generation "Whatever Worked"	1830-1930	HCs, NH_3, CO_2
2nd Generation "Safety and Durability"	1931-1990	CFCs, HCFCs (e.g., R-12, R-22)
3rd Generation "Ozone Protection"	1990-2010s	HFCs (e.g., R-410A, R-134a)
4th Generation "Global Warming"	2010-future	Low-GWP HFCs (e.g., R-32), HFOs (e.g., R-1234yf), HCs, others

Source: Calm (2008)[59]

The growing international emphasis on global warming mitigation has stimulated interest in a fourth generation of refrigerants that have low GWP, such as hydrofluoroolefins (HFO). This fourth generation also includes a revisit to previously explored refrigerants, including R-32, carbon dioxide, and HCs. R-410A, a third-generation, high-GWP HFC, is a blend, which includes R-32, that was developed to address the mild flammability of R-32. Advances in safety have allowed the use of pure R-32 and other mildly flammable and flammable refrigerants in certain applications, though safety standards will have to be updated in order to enable the safe use of these refrigerants in larger systems.

Table 4-2: Summary of Refrigerant Environmental Properties

Refrigerant Type	Ozone Depletion Potential	Global Warming Potential
CFC	High	Very High
HCFC	Very Low	Very High
HFC	Zero	High
HFO	Zero	Lower
HC	Zero	Negligible
CO_2	Zero	Negligible

Source: Adapted from *Refrigerants, Naturally!*[60]

Building on the success of the CFC and HCFC phasedowns, the international community is working to address the global warming impact of HFC refrigerants while maintaining equipment safety and cost effectiveness by amending the Montreal Protocol and updating domestic refrigerant policies. Section 8 describes these efforts.

59Calm, James. 2008. "The Next Generation of Refrigerants - Historical Review, Considerations, and Outlook," 1123–33. Available at: http://www.jamesmcalm.com/pubs/Calm%20JM,%202008.%20The%20Next%20Generation%20of%20Refrigerants%20-%20Historical%20Review,%20Considerations,%20and%20Outlook,%20IJR.pdf

60 Refrigerants Naturally. n.d. "Natural Refrigerants." Accessed April 2016. Available at: http://www.refrigerantsnaturally.com/natural-refrigerants/. Refrigerants, Naturally! is an initiative of companies in the food, drink, foodservice and consumer goods sectors seeking to reduce the direct climate impact of refrigeration and is supported by UNEP. A qualitative characterization of HFOs was added to the table.

4.2 Refrigerant Selection Criteria

Several practical considerations limit the number of refrigerants that may be viable for widespread usage out of the thousands of possible natural and artificial fluids. A/C manufacturers must balance the thermodynamic performance (e.g., capacity, temperature, efficiency) of each refrigerant as well as considerations for safety (e.g., pressure, toxicity, and flammability), compatibility with system materials, availability, cost, and environmental impact. Therefore, the industry generally adopts a limited number of refrigerants for each application, and often builds consensus around a single refrigerant for specific equipment types.

Figure 4-1 highlights the challenge of selecting a refrigerant for each A/C application, by comparing the major attributes of two refrigerants common in today's equipment, R-22 and R-410A, and two potential alternatives, CO_2 and R-32, which introduce tradeoffs. The figure qualitatively compares all four to a theoretical ideal refrigerant on ten different characteristics (a score of 1 is ideal) based on the authors' experience and judgement. The tradeoffs of the refrigerants include:

- **R-22** is a common HCFC refrigerant for residential and commercial unitary A/C systems due to its performance characteristics. Due to its non-zero ODP and high-GWP (1,760), developed countries have largely phased out R-22 and developing countries are accelerating their own phase-out (see Section 8).
- **R-410A** is a HFC refrigerant with zero ODP that serves as a replacement for R-22 in most residential and commercial unitary A/C systems. R-410A's key deficiency is its high-GWP (1,924).
- **CO_2** is attractive due to its low GWP (1); however, it typically introduces additional design complexities due to its, high operating pressure, lower cooling capacity, and lower thermodynamic cycle efficiency at high ambient temperatures.
- **R-32** is an HFC that has a lower GWP (677) than R-410A, but is mildly flammable, which has the potential to add design complexity in order to ensure safety of technicians and building occupants.

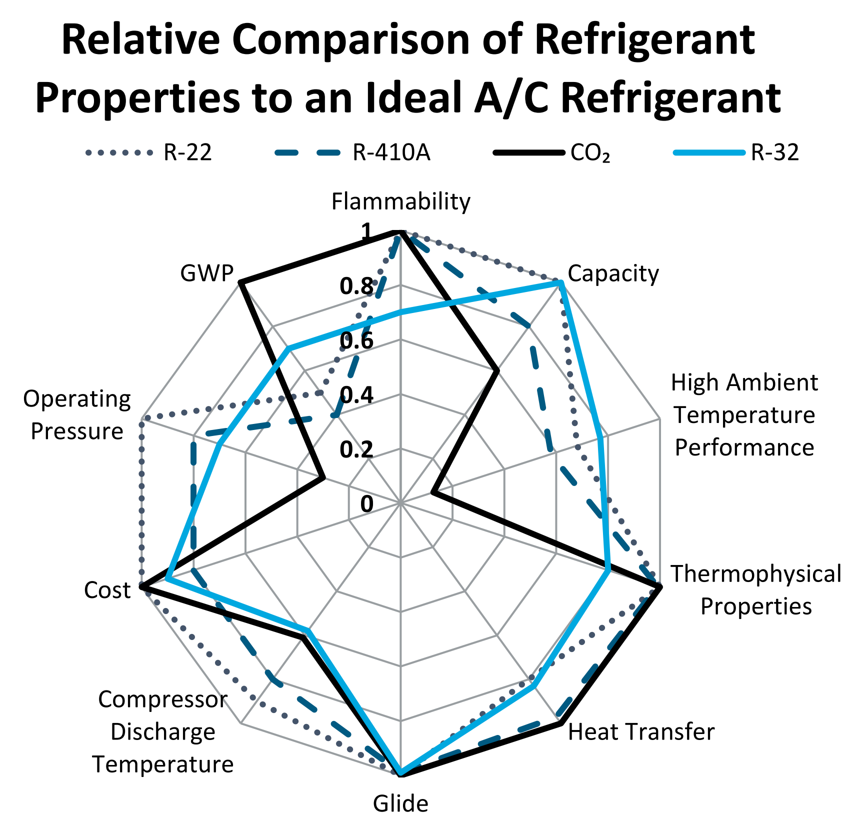


Figure 4-1: Comparison of refrigerants to an ideal A/C refrigerant[61] (score of 1 is ideal)

Replacing the current generation of A/C systems that use high-GWP HFC refrigerants requires careful consideration of the tradeoffs associated with each of the low-GWP refrigerant options. Together, the industry and research community have identified numerous potential alternative refrigerants that meet many of the necessary characteristics, including lower GWP; however, barriers remain for many of those alternatives before they are deployable at commercial scale. McLinden et al. (2014) screened over 50,000 potential molecules for thermodynamic performance, which revealed 1,200 candidate refrigerants.[17] Manufacturers continue to invest in R&D to address some or all of the following for each of the identified potential alternatives:

- Flammability
- Cooling capacity and energy efficiency
- Performance at high-ambient temperatures
- System cost (discussed in Section 6)

[61] This figure provides a qualitative comparison of a refrigerant's properties relative to those of a theoretical ideal refrigerant based on the authors' experience and judgement. The plot of individual characteristics may indicate higher values (e.g., operating pressure, cost, GWP, etc.) or lower values (e.g., capacity, heat transfer, etc.). Figure derived from analysis by Pham, Hung, and Harvey Sachs. 2010. "Next Generation Refrigerants: Standards and Climate Policy Implications of Engineering Constraints." Available at: http://aceee.org/files/proceedings/2010/data/papers/1933.pdf.

4.2.1 Flammability

Because some residential and most commercial A/C equipment require relatively large refrigerant charges and commonly operate in enclosed public spaces, safety is a key consideration for refrigerant selection. Some potential replacement candidates introduce flammability challenges that the A/C industry, building owners, and occupants have not previously had to address. However, updated safety standards and regulations can mitigate risks associated with flammable refrigerants by specifying A/C system design constraints (e.g., refrigerant leakage sensors, charge limits) or building features (e.g., ventilation systems).

Developing the proper safeguards for flammable refrigerants requires careful coordination amongst many standards organizations and government bodies. Figure 4-2 highlights the various stakeholder groups involved in the safe use of A/C refrigerants in the U.S.[62] This complex process also occurs internationally through the International Organization for Standardization (ISO), the International Electrotechnical Commission (IEC), and a variety of country-specific standards. The process can take over a decade from the first approved revisions to final building code adoption.[63] DOE is funding research and development efforts in collaboration with AHRI and ASHRAE to build a single, comprehensive body of knowledge on the safe use of flammable low-GWP refrigerants.[64] The program is designed so that ASHRAE, International Code Council (ICC), and other standards organizations can use this information to fast-track revisions to the safety standards, and accelerate low-GWP refrigerant adoption globally.

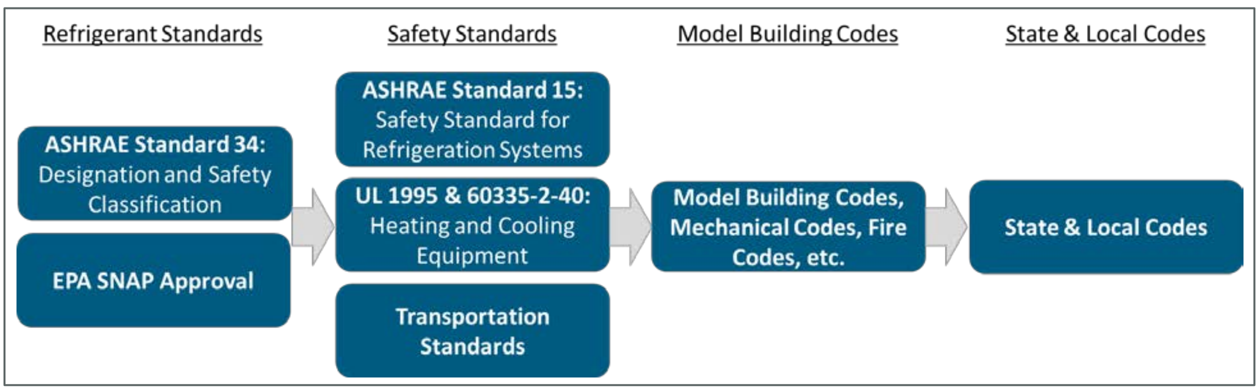


Figure 4-2: U.S. refrigerant standards and codes (and associated organizations)[62]

ASHRAE Standard 34-2013 defines refrigerant safety group classifications for toxicity and flammability as follows:

Flammability classes
- 1 – No flame propagation
- 2L – Lower flammability
- 2 – Flammable
- 3 – Higher flammability

Toxicity groups:
- A – Nontoxic
- B – Toxic

[62] Figure adapted from Rajecki, Ron. 2015. "Carefully Embracing Flammable Refrigerants - Additional Uses for Flammable Refrigerants Require Approval Process." ACHR News. March 30, 2015. Available at: http://www.achrnews.com/articles/129241-carefully-embracing-flammable-refrigerants
[63] Carrier Corporation. 2015. "New Refrigerants Impact Standards and Codes." Carrier Engineering Newsletter. Volume 3, Issue 2. 2015. Available at: dms.hvacpartners.com/docs/1001/Public/0E/ENG_NEWS_3_2.pdf
[64] ASHRAE. 2016. "ASHRAE, AHRI, DOE Partner to Fund Flammable Refrigerant Research." Accessed June 2016. Available at: https://www.ashrae.org/news/2016/ashrae-ahri-doe-partner-to-fund-flammable-refrigerant-research.

Today's A/C systems primarily use A1 refrigerants, and current research efforts focus on low-GWP refrigerants in the A1, A2L, and A3 safety classes. Table 4-3 lists GWP values for the range of low-GWP refrigerant options as alternatives for some of today's common refrigerants. Compared to today's high-GWP refrigerants, some of the available alternative refrigerants could reduce the GWP for A/C refrigerants by 90% or more. Technically suitable alternatives exist for most A/C applications and manufacturers are beginning to debut products for select A/C equipment types using some of the available alternative refrigerants (see Table 4-7).

Table 4-3: 100-Year GWPs for AHRI/AREP Alternative Refrigerants

Safety Group	GWP Ranges for Alternatives to:		
	R-134a *(GWP: 1,300)*	R-22, R-404A, R-407C, and R-507A *(GWP range: 1,624-3,942)*	R-410A *(GWP: 1,924)*
A1	1 – 860	1 – 1,445	1 – 1,445
A2L	< 1 – 107	124 – 989	< 1 – 708
A3	3	3	3

Source: Table compiled from different AHRI / AREP presentations on potential refrigerant alternatives including UNEP Webinar (2013),[65] AHRI AREP Phase 1 (2014)[66] and AHRI AREP Phase 2 (2016)[67]
Note: Few alternative refrigerants classify in the A2 safety group.

Strategies to limit the refrigerant charge in smaller self-contained equipment categories (e.g., window A/C) minimize the ignition risk. For example, for small hermetically sealed equipment, manufacturers have developed safe solutions using A3 refrigerants. Such solutions are inadequate as a primary solution for higher capacity A/C systems having larger refrigerant charges. For equipment categories, like ducted split residential A/C, many promising low-GWP refrigerants are moderately flammable (A2L safety class), and have limited availability to date. At a workshop at the National Institute for Standards in Technology (NIST) in 2014, industry researchers and other safety experts developed a roadmap to investigate strategies to mitigate the risks of flammable refrigerants.[68] Many of the issues they identified are focus areas for the aforementioned R&D collaboration between DOE, AHRI, and ASHRAE.

Some of the most important activities identified at the workshop include:

1. Develop a document outlining the information and steps required for safe implementation of marginally flammable refrigerants.

[65] Amrane, Karim. 2013. "Overview of AHRI Research on Low GWP Refrigerants." Available at: http://www.unep.org/ozonaction/Portals/105/documents/webinar/2013/14August2013_Ppt_Karim%20Amrane.pdf.
[66] AHRI. 2014. "AHRI-Low-GWP AREP Conference." In New York, New York. Available at: http://www.ahrinet.org/site/517/Resources/Research/AHRI-Low-GWP-Alternative-Refrigerants-Evaluation-Program/AHRI-Low-GWP-AREP-Conference
[67] AHRI. 2014. "AHRI Low Global Warming Potential Alternative Refrigerants Evaluation Program." Available at: http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP2014Conference/1_AHRI_Low-GWP_AREP_Opening.pdf.
[68] Linteris, Gregory, and Jeffrey Manion. 2015. "Workshop on the Research Needs Concerning the Exothermic Reaction of Halogenated Hydrocarbons." National Institute of Standards and Technology. Available at: http://www.nist.gov/customcf/get_pdf.cfm?pub_id=918023.

2. Develop a list of possible, plausible, and most common scenarios in which a refrigerant-air mixture might be ignited, so that the risk and consequences can be determined.
3. Determine the ignition properties of marginally flammable refrigerants with air.
4. Develop accurate, validated correlations and modeling capabilities for specifying venting requirements to prevent overpressure from flames of marginally-flammable refrigerants.
5. Improve sensors for detection of refrigerant gases or their decomposition byproducts.

4.2.2 Cooling Capacity and Energy Efficiency

Laboratory testing has revealed that several low-GWP alternatives can meet or exceed the capacity and efficiency (within 5-10%) of current high-GWP refrigerants, with only “soft optimization.”[11] These results are encouraging because they indicate potential reductions to indirect emissions (which represent the majority of lifecycle GHG emissions from A/C systems), in addition to reductions to CO_2-equivalent refrigerant emissions for the next generation of A/C systems. Reductions in operating costs from increased energy efficiency will additionally help offset potential upfront cost increases of low-GWP systems. The efficiency of A/C systems is likely to improve further as manufacturers fully optimize them for low-GWP refrigerants.

To understand how different refrigerant alternatives affect the capacity and efficiency of common A/C equipment categories, AHRI initiated the AHRI Low-GWP AREP. The program’s goal is to provide relative performance results to guide future research. The program evaluated several refrigerants in representative A/C systems, either as a “drop-in” replacement (i.e., minor charge or compressor speed adjustments) or with only “soft” system optimization (i.e. minor modifications for compressor size/speed, flow control/expansion valve sizing, lubrication type, piping/heat exchanger size, etc.).

Table 4-4 highlights the results of one test series on a 14 kW_{th} (4 ton) packaged rooftop unit that was designed for R-410A and soft optimized for various low-GWP alternatives. Each of the three low-GWP alternatives (DR-55, R-32, DR-5A) showed improved system efficiency versus the R-410A baseline, while using less refrigerant (i.e., smaller charge) and maintaining similar capacity (achieved using only modest changes to the thermal expansion valve [TXV] and compressor speed).

Table 4-4: Packaged RTU A/C Test Results with R-410A Alternatives

Refrigerant	GWP	AHRI A Conditions (35.0°C [95°F])		
		Charge, kg (lbm)	Capacity, kW_{th} (kBtu/hr.)	COP, W/W (EER, Btu/W-hr.)
R-410A (Baseline)	1,924	4.1 (9.0)	16.2 (50.2)	3.32 (11.32)
DR-55 (R-452B)	675	-9%	-0.1%	+4.3%
R-32	677	-19%	+0.9%	+5.8%
DR-5A	466	-9%	+0.8%	+4.6%

Source: Schultz et al. (2015)[69]

Oak Ridge National Laboratory (ORNL) found similarly promising results in testing of low-GWP refrigerants in a 5.25 kW_{th} (1.5 ton) ductless mini-split A/C designed for R-410A. Table 4-5 shows that with only soft-optimization, several alternative refrigerants provide similar or improved efficiency (COP) and capacity compared to the R-410A baseline. In particular, R-32 and DR-55 showed improved efficiency at both outdoor test conditions. The researchers note that manufacturers can typically overcome performance losses of up to 5% through further soft-optimization, whereas 10% losses may require additional engineering, and losses greater than 10% may require complete unit redesign.[70]

Table 4-5: Mini-Split A/C Test Results of R-410A Alternatives at Various Outdoor Conditions

Refrigerant	GWP	AHRI B Conditions (27.8°C [82°F])		AHRI A Conditions (35.0°C [95°F])	
		COP (W/W)	Capacity (kW_{th})	COP (W/W)	Capacity (kW_{th})
R-410A (Baseline)	1,924	3.95	5.35	3.40	5.14
R-32	677	+1%	+2%	+4%	+5%
DR-55 (R-452B)	675	+2%	-4%	+3%	-3%
L41	572	-8%	-16%	-5%	-14%
ARM-71A	461	0%	-7%	-1%	-8%
HPR-2A	593	-7%	-12%	-2%	-9%

Source: Abdelaziz and Shrestha (2016)[70]

4.2.3 Performance at High-Ambient Temperatures

Results of testing at high-ambient-temperature (HAT) conditions suggest the potential to continue to improve system efficiency while reducing refrigerant GWP, even in hot, tropical and

[69] Schultz, Ken, Marcos Perez-Blanco, and Steve Kujak. 2015. "System Soft-Optimization Tests of Refrigerant R-32, DR-5A, and DR-55 in a R-410A 4-Ton Unitary Rooftop Heat Pump-Cooling Mode Performance." Available at: http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP_Final_Reports/AHRI_Low_GWP_AREP_Rpt_056.pdf.
[70] Abdelaziz, Omar, and Som Shrestha. 2016. "Soft-Optimized System Test of Alternative Lower GWP Refrigerants in 1.5-Ton Mini-Split Air Conditioning Units." Available at: http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP_Final_Reports/AHRI_Low_GWP_AREP_Rpt_062.pdf.

desert regions. The AHRI test conditions in Table 4-5, above, are representative of North American and European climates (35.0°C / 95°F). Because most future cooling demand growth will occur in regions with hot climates, it is important to consider A/C system performance at high ambient temperatures when evaluating alternative refrigerants. Low-GWP AREP testing conducted by Oak Ridge National Laboratory has found that several alternative refrigerants provide similar to higher capacities and efficiencies at high ambient temperatures compared to R-410A, the most common HFC A/C refrigerant.

Low-GWP AREP testing at HAT conditions included test series at 52.0°C (125.6°F) and 55.0°C (131°F) using a 5.25 kW_{th} (1.5 ton) ductless mini-split A/C using R-410A. Most of the candidate refrigerants shown in the table exhibited improvements to efficiency and/or capacity at high ambient temperatures relative to the baseline tests using R-410A. This is mainly due to the alternatives exhibiting lower degradation rates for capacity and efficiency compared to R-410A as outdoor temperatures increase.[11] Similar testing of alternative refrigerants in a ductless mini-split A/C designed for R-22 showed improved efficiency using R-290 at all ambient conditions while the other alternative refrigerants had mixed results.

Table 4-6: Mini-Split A/C Test Results of R-410A Alternatives at High-Ambient Conditions

Refrigerant	GWP	Hot Ambient Conditions 52.0°C (125.6°F)		Extreme Ambient Conditions 55.0°C (131°F)	
		COP (W/W)	Capacity (kW_{th})	COP (W/W)	Capacity (kW_{th})
R-410A	1,924	2.07	3.98	1.87	4.76
R-32	677	+5%	+11%	+6%	+13%
DR-55 (R-452B)	675	+3%	0%	+3%	0%
L41	572	+3%	-6%	+5%	-3%
ARM-71A	461	+2%	-4%	+2%	-3%
HPR-2A	593	+5%	-1%	+6%	+1%

Source: Abdelaziz and Shrestha (2016)[71]

Laboratory results for both temperate and high-ambient temperature climates suggest that it is possible to maintain or even improve A/C system efficiency while transitioning to low-GWP refrigerants, providing compounding benefits of reduced direct and indirect emissions, as well as lower operating costs.

4.3 Low-GWP Products and Private Sector R&D Efforts

Products using low-GWP refrigerants and having comparable or improved efficiency and performance relative to today's typical equipment are commercially available in four major A/C equipment categories (see Table 4-7). These four equipment categories have refrigerant options with GWPs of less than 10. Current regulations and safety codes inhibit or set specific

[71] Abdelaziz et al. 2015. "Alternative Refrigerant Evaluation for High-Ambient-Temperature Environments: R-22 and R-410A Alternatives for Mini-Split Air Conditioners." October 2015. Accessed March 2016. Available at: http://energy.gov/sites/prod/files/2015/10/f27/bto_pub59157_101515.pdf

conditions on the use of certain of these refrigerants in certain equipment types and in specific markets due to their flammability, so availability is regional. However, building codes and other regulations are continually evolving as governments and other organizations look for ways to allow for safe use of these refrigerants.

Table 4-7: Status of A/C Equipment Categories with Low-GWP Refrigerant Options Showing Comparable or Improved Performance and Efficiency[72]

	Equipment	Status	Approved for use in U.S.	U.S. SNAP Application Submitted	Example		2012 Global Annual Sales (US$B)
					Best GWP	Detail	
Residential	Room and portable	●	✓	✓	<10	R-290; R-32	$3.4
Residential	Ducted split & single-package	◔		✓	<700	Multiple candidates	$3.3
Residential	Ductless split system	●		✓	<10	R-32; R-290	$48.5
Commercial	Packaged terminal	◑	✓	✓	<700	R-32	$0.2
Commercial	Packaged rooftop unit	◔		✓	<700	Multiple candidates	$4.6
Commercial	Ductless (VRF/VRV)	◑			<700	R-32	$10.7
Commercial	Scroll / recip. chiller	◑		✓	<700	DR-55 (R-452B)	$8.3 (all chillers)
Commercial	Screw chiller	●	✓	✓	<10	R-513A; R-1234ze(E)	
Commercial	Centrifugal chiller	●	✓	✓	<10	R-1233zd(E), R-1234ze(E)	

Source for market size: Approximate 2012 global sales data (includes equipment using all refrigerants) from BSRIA;[73] U.S approval status from EPA website[74]

● Commercially available in some global markets; ◑ Product under development; ◔ Tested in Lab

Many global A/C manufacturers have announced product development plans or funding commitments to introduce A/C systems using low-GWP refrigerants for a variety of applications. The following list highlights only a small portion of these efforts:

- AHRI reports that the industry plans to spend at least $5 billion over 10 years on R&D for low-GWP refrigerants and equipment.[75]

[72] Full citations are available in Appendix C: Low-GWP A/C Equipment Status
[73] BSRIA. Anette M. Holley. AHR, 29 January 2013. "Global Trends in Air Conditioning." http://www.slideshare.net/BSRIA/hvacr-2013-analysing-world-markets; "Ducted Standard Splits" included with VRF; "Indoor Packaged" included with "Rooftops"; PTAC (subtracted from "Room") estimate from BSRIA. Alfonso Olivia. January 2014. "BSRIA in US and AC Trends." Accessed June 2016. Available at: http://www.slideshare.net/BSRIA/air-conditioning-usa-2014-ahr-expo-edited-market-research
[74] EPA. 2016. "Refrigeration and Air Conditioning." List of acceptable substitutes by end use. Accessed June 2016. Available at: https://www.epa.gov/snap/refrigeration-and-air-conditioning.
[75] Gargaro, Kyle. 2014. "HVAC Industry Commits $5 Billion to Refrigerant Plan." Available at: http://www.achrnews.com/articles/127699-hvac-industry-commits-5-billion-to-refrigerant-plan.

- Trane / Ingersoll Rand debuted air-cooled chillers in 2015 for several global markets using XP-10 (R-513A) as a replacement for R-134a.[76]
- Johnson Controls announced the availability of centrifugal and screw chillers using XP-10 (R-513A) as a replacement for R-134a.[77]
- Daikin / Goodman plans to debut a self-contained packaged terminal air conditioner (PTAC) using R-32 for North America in 2016.[78]
- Honeywell anticipates spending a total of more than $880 million on R&D through 2025 to shift refrigerant production to low-GWP alternatives.[79]
- Carrier debuted a water-cooled screw chiller in Europe using R-1234ze(E) as a replacement for R-134a.[80]

Equipment OEMs, component suppliers, refrigerant manufacturers, and industry researchers have taken proactive steps such as Low-GWP AREP to compile a body of research from which to develop additional products and inform safety codes and government policies on refrigerants. R&D efforts underway today will help develop low-GWP technologies and risk mitigation strategies for many larger residential and commercial A/C products (e.g., central split-systems, rooftop units, chillers), especially replacements for R-410A equipment. The following list provides several examples of R&D projects and commitments from leading A/C manufacturers. It highlights only a small portion of the research that organizations have undertaken:

- Over 35 organizations participated in the industry-lead Low-GWP AREP program by supported testing on dozens of alternative refrigerants for different A/C and refrigeration systems[81]:

- Arkema, Inc.
- ARMINES-MINES ParisTech
- BITZER
- Bristol Compressor International Inc.
- Carrier Corporation
- Carlyle Compressor
- Chemours Co.
- Climate Master
- Comstar International, Inc.
- Daikin Applied Americas, Inc.
- Daikin Industries Ltd
- Danfoss
- Embraco Brazil
- Embraco Slovakia Sro
- Emerson Climate Technologies
- Friedrich Air Conditioning Company, LTD.
- Goodman Manufacturing
- Hillphoenix
- Honeywell International, Inc.
- Hussmann
- Johnson Controls, Inc.
- Kold- Draft International, LLC
- Lennox Industries Inc.
- LG Electronics
- Manitowoc Ice, Inc.
- Mexichem Fluor, Inc.
- National Refrigerants, Inc.
- Oak Ridge National Laboratory
- Shanghai Hitachi Electrical Appliances CO.,LTD
- Tecumseh Company Co.

76 Trane. 2015. "Trane Sintesis Air-Cooled Chillers are Now Available to Help Reduce Greenhouse Gas Emissions." June 15, 2015. Available at: http://www.trane.com/commercial/north-america/us/en/about-us/newsroom/press-releases/trane-sintesis_-air-cooled-chillers-are-now-available-to--help-r.html
77 Johnson Controls. 2016. "Johnson Controls Advances Environmental Sustainability with Chiller Platforms Compatible with Low GWP Refrigerants." Accessed April 2016. Available at: http://www.johnsoncontrols.com/media-center/news/press-releases/2016/01/20/advanced-environmental-sustainability-with-chiller-platforms-compatible-with-low-gwp-refrigerants.
78 Daikin. 2015. "White House Recognizes Air Conditioner and Chemical Manufacturer Daikin for Commitment to Reduce Greenhouse Gas Emissions." October 16, 2015. Available at: http://www.daikin.com/press/2015/151016/
79 Gargaro, Kyle. 2014. "HVAC Industry Commits $5 Billion to Refrigerant Plan." Available at: http://www.achrnews.com/articles/127699-hvac-industry-commits-5-billion-to-refrigerant-plan.
80 Gaved, Andrew. 2016. "Carrier Opts for HFO 1234ze Refrigerants for Global Chiller Range." February 26, 2016. Available at: http://www.racplus.com/news/carrier-opts-for-hfo-1234ze-refrigerants-for-global-chiller-range/10003440.fullarticle
81 AHRI Low Global Warming Potential Alternative Refrigerants Evaluation Program – Conference Open January 2016

- Thermo King / Ingersoll Rand
- Trane/ Ingersoll Rand
- University of Maryland
- WaterFurnace International Inc.
- Zamil Air Conditioners

- Several Middle Eastern manufacturers participated in the UNEP-UNIDO project of promoting low-GWP refrigerants for the A/C sectors in high-ambient temperature countries (PRAHA for the Persian Gulf market, and EGYPRA for the Egyptian market),[82] including Alessa, AWAL Gulf, Coolex RIC, GAMI, Petra, SKM, and Zamil.[83]

Section 7 discusses additional private sector and government-sponsored R&D efforts on new air conditioning technologies that are energy efficient and utilize near-zero-GWP refrigerants or move beyond refrigerants altogether.

[82] Elassaad, Bassam. 2015. "Suitable Alternatives at High-Ambient Temperatures for Small and Middle-Size AC Equipment." presented at the Workshop on Management of HFCs: Technical Issues, Bangkok, Thailand.

[83] UNEP. 2014. "Promoting Low-GWP Refrigerants for Air-Conditioning Sectors in High-Ambient Temperature Countries (PRAHA)." United Nations Environmental Programme. Available at: http://www.unep.org/ozonaction/Portals/105/documents/events/MOP26/Fact%20Sheet%20Promoting%20low-GWP%20Refrigerants%20for%20Air-Conditioning%20Sectors%20in%20High-Ambient%20Temperature%20Countries%20(PRAHA).pdf.

5 Energy Efficiency Improvements

In addition to advancing low-GWP refrigerants, the A/C industry has steadily improved the energy efficiency of A/C systems through a combination of technological innovation and market transformation strategies. Manufacturers have introduced several component technologies that improve overall system efficiency, including: multi-stage compression and variable-speed drives, novel compressor, fan, motor, and heat exchanger designs, electronic expansion valves, and advanced controls. Various government and industry programs have also significantly increased the demand and overall adoption of high-efficiency A/C systems, including minimum efficiency standards such as DOE's appliance standards, comparative and endorsement labels such as ENERGY STAR, public challenges and awards, and incentive programs. Such innovations are a key component to reducing A/C impacts on the climate, as they make a substantial impact on indirect emissions. Further, comprehensive approaches to implement effective refrigerant management practices, high-performance building design, and renewable energy integration can further reduce direct and indirect emissions for A/C systems.

5.1 Air Conditioning Energy Efficiency Trends

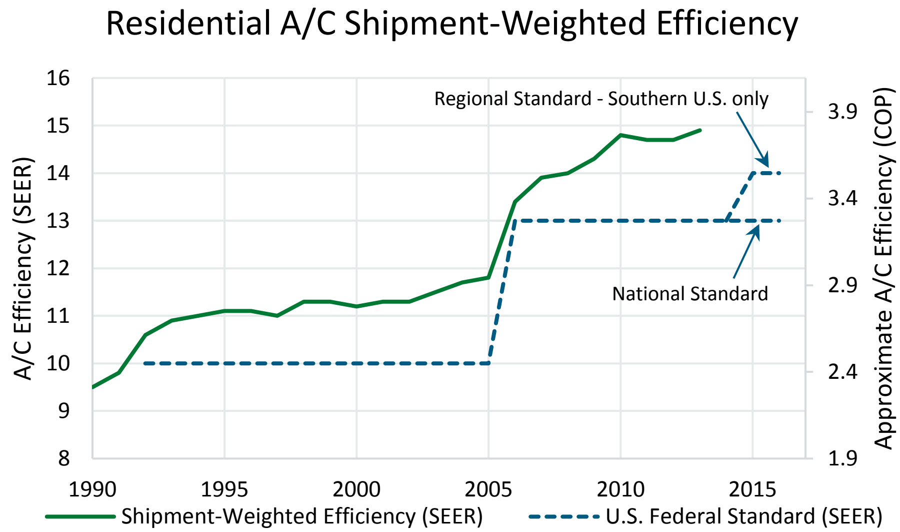
Residential and commercial A/C systems have seen significant performance and efficiency improvements over the last 25 years, leading to corresponding decreases in operating costs. Improving A/C system efficiency also reduces indirect CO_2 emissions caused by electrical generation, which account for the majority of an A/C system's climate impact (see Section 3). Since the early 1990s, manufacturers have innovated to improve efficiency for both baseline and premium equipment. Today, premium efficiency products in the U.S. can reach the following efficiency levels or greater: [84, 85]

- Residential ducted central A/C: 4.8 COP (26 SEER)
- Commercial rooftop units: 4.0 COP (17.5 SEER / 21 IEER)
- Ductless mini-splits: 4.5 COP (25 SEER)

Figure 5-1 reports the average efficiency of residential A/C systems sold in the U.S. in recent years, in terms of SEER and seasonal COP. This long-term trend of increasing efficiency coincides with the industry transition from CFC and HCFC refrigerants to zero ODP HFC alternatives. A/C efficiency improvements also benefit the greater electrical grid infrastructure by reducing peak demand, which is a key consideration in both developed and developing countries.

[84] SEER = Seasonable Energy Efficiency Ratio; IEER = Integrated Energy Efficiency Ratio; Cooling SEER and EER ratings from AHRI product database and conversion from and EER to COP conversion factor of EER = 3.412 COP. AHRI Directory of Certified Product Performance Accessed March 2016. https://www.ahridirectory.org/ahridirectory/pages/home.aspx

[85] A/C equipment efficiencies (SEER, COP) are not directly comparable across equipment types or countries due to differing climate, technical specifications and test procedures.



Source: Groff (2014)[86], Cutler et al. (2013)[87], DOE Rulemaking Documents[88, 89]

Figure 5-1: Shipment weighted A/C efficiency for residential CACs

Numerous governments, utilities, and consumer programs have helped increase adoption of more energy efficient products, including:

- **Government-established efficiency standards** establish a mandatory efficiency minimum that all equipment manufactured and sold in that country must meet or exceed. U.S. DOE has regularly increased the minimum standards for different A/C product types as innovations improved the cost-effectiveness of more efficient components and systems. DOE expects that recently updated standards for commercial HVAC systems will save more energy than any standard issued by DOE to date, and save businesses $167 billion in utility costs.[90] European Union standards currently specify different efficiency levels for A/C systems using high-GWP (> 150) and low-GWP (< 150) refrigerants.[91] (See Section 8 for additional discussion of regulations.)
- **Comparative and endorsement labeling programs**, such as ENERGY STAR in the U.S., Top Runner in Japan, or EU-wide labels enable equipment specifiers and building owners to identify quickly the products that are more efficient. The example European Union A/C efficiency label in Figure 5-2 provides easy-to-read guidance on how a

[86] Groff, Gerald. 2014. "Heat Pumps in North America 2014." IEA/OECD Heat Pump Centre Newsletter. Vol. 32, No. 3. 2014. Available at: http://www.nachhaltigwirtschaften.at/iea_pdf/newsletter/iea_hpc_newsletter_no_3_2014.pdf.

[87] Original data in SEER; conversion is solely for conveying approximate impact to international audiences, but is generally considered to be an imprecise conversion. Cooling SEER to EER using de-rating estimates from Table 6 of Cutler et al. (2013) and EER to COP conversion factor of EER = 3.412 COP. Exact SEER to COP/EER conversions vary depending on local climate. Cutler et al. 2013. "Improved Modeling of Residential Air Conditioners and Heat Pumps for Energy Calculations." National Renewable Energy Laboratory (NREL). NREL/TP-5500-56354. January 2013.

[88] DOE. 2011. "Technical Support Document: Energy Efficiency Program for Consumer Products: Residential Central Air Conditioners, Heat Pumps, and Furnaces." https://www.regulations.gov/document?D=EERE-2011-BT-STD-0011-0012.

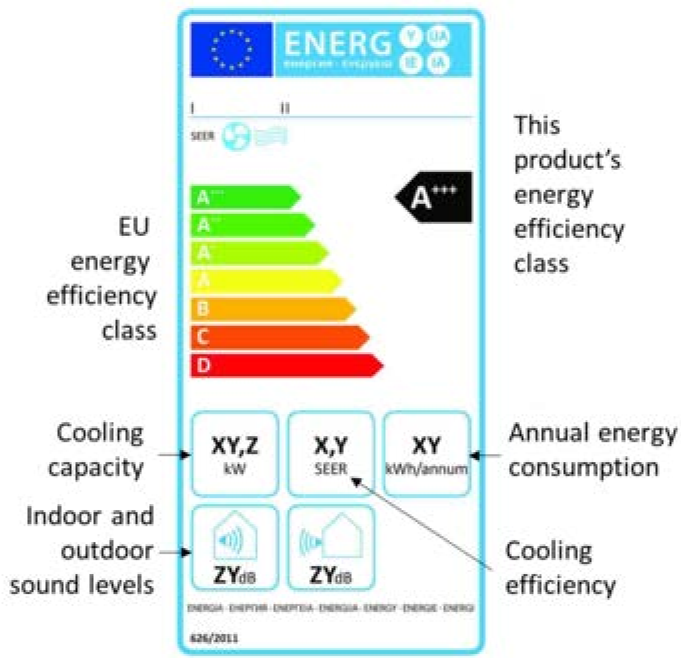
[89] Beginning in 2015, DOE introduced higher efficiency standards for residential A/C equipment sold in states in the Southeastern and Southwestern U.S. http://energy.gov/gc/regional-standards-enforcement

[90] DOE. 2016. "Energy Department Announces Largest Energy Efficiency Standard in History." http://energy.gov/articles/energy-department-announces-largest-energy-efficiency-standard-history Efficiency standards and projected energy savings include commercial air-cooled air conditioners, heat pumps, and warm air furnaces.

[91] EU labeling for A/C systems. Accessed April 2016. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012R0206

product compares on energy efficiency, indoor and outdoor sound ratings, and other features. Today, over 70 countries participate in labeling programs for A/C equipment.[92]

- **Public challenges, competitions, and awards** (e.g., U.S. ENERGY STAR Most Efficient, Japan's Energy Conservation Grand Prize, the Clean Energy Ministerial's Super-Efficient Equipment and Appliance Deployment Initiative [SEAD]) can also spur technology development and adoption by highlighting manufacturers and building owners who reach performance or installation milestones.
- **Utility energy efficiency programs** also support the adoption of high efficiency A/C systems by providing rebates and other incentives to building owners to help offset the incremental cost for high-performance equipment.



Source: European Union Labeling Program (2011)[93]

Figure 5-2: Example European Union A/C efficiency label

5.2 Efficient Air Conditioning Component Technologies

The sustained efficiency improvements over the last 25 years are not due to any single technology, but rather the steady evolution of several technologies that have collectively increased the efficiency of A/C systems. Table 5-1 highlights some of the major component technologies that have improved the efficiency of many residential and commercial A/C product categories. Today, manufacturers have incorporated these component technologies into their product lineups, such as ductless mini-split A/Cs using inverter-driven variable-speed compressors and fans, and commercial rooftop units with microchannel heat exchangers and advanced controls for economizer "free cooling" and demand-controlled ventilation. Typically, manufacturers introduced these components and capabilities to premium products first, before

[92] CLASP Global S&L Database Accessed February 2016. http://clasp.ngo/Tools/Tools/SL_Search/SL_SearchResults
[93] EU labeling for A/C systems. Accessed April 2016. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012R0206

cost reductions enabled their widespread usage for high-volume, baseline systems. To operate with new low-GWP alternative refrigerants, manufacturers can further optimize each component to provide high efficiency performance. Moreover, standards, labeling programs and incentives can drive further efficiency improvements and reductions in lifecycle cooling costs.

Table 5-1: Efficient A/C Component Technologies

AC Component	Description and Efficiency Benefits
Multi-Stage and Variable-Speed Drives/Controls	Electronic motor controls have enabled substantial energy efficiency improvements on compressor and fan motors through variable-speed operation. By modulating motor speed on compressors, the A/C system can more closely match the part-load cooling demand and improve seasonal efficiency by reduce cycling losses that are common during the majority of the cooling season when the system's full capacity is not required.[94] Similarly, variable-speed controls operate fans motors at their most efficient setting to meet the airflow needs of the system.
Advanced Compressors	A/C compressor efficiency and performance has steadily improved as manufacturers incrementally improved current designs (e.g., high efficiency reciprocating) and introduced entirely new compressor technologies (e.g., scroll, rotary). In addition, larger systems use multiple compressors to stage capacity and improve part-load performance.
Improved Heat Exchangers	Metal tube-and-fin heat exchangers are the most common in A/C systems for transferring heat between the refrigerant and air. Manufacturers have increased the size of heat exchangers to improve system efficiency, especially during part-load operation. Advanced heat exchanger designs, such as microchannel heat exchangers and other small diameter designs, have further improved system efficiency, while also reducing refrigerant charge, fan energy consumption, and physical size.
Electronic Expansion Valves	Expansion valves control the amount of refrigerant flowing through the evaporator to maintain proper system conditions. Thermostatic expansion valves (TXV) improve upon earlier static capillary tube and fixed orifice expansion devices by modulating refrigerant flow based on refrigerant superheat temperature at the evaporator exit. Newer electronic expansion valves (EEV) provide increased modulation capabilities to match more closely the needs of variable-capacity A/C systems.
High Efficiency Fans	Fan energy consumption has decreased over time as many systems have incorporated more aerodynamic component designs (e.g., fan blades, condensing unit housing), high efficiency motors, and variable-speed controls.[95] Manufacturers have applied these innovations to axial and centrifugal fans for both heat exchange as well as distribution of conditioned air throughout buildings.
High Efficiency Motors	Electric motors are core components for A/C compressors and fans, and improved motor designs have a significant impact on overall A/C system efficiency. Electrically commutated motors (ECM) have higher efficiencies than permanent split capacitor (PSC) motors for A/C fans and operate at a wider range of conditions using electronic controls.
Advanced Controls	Beyond simple thermostatic set-point controls, A/C systems have incorporated advanced control schemes and hardware to improve system efficiency. Different occupancy sensing strategies can automatically alter thermostat set-points when building occupants are away to reduce energy consumption. Economizer controls enable A/C systems to use cooling energy from ventilation air or chilled-water cooling towers when conditions allow.

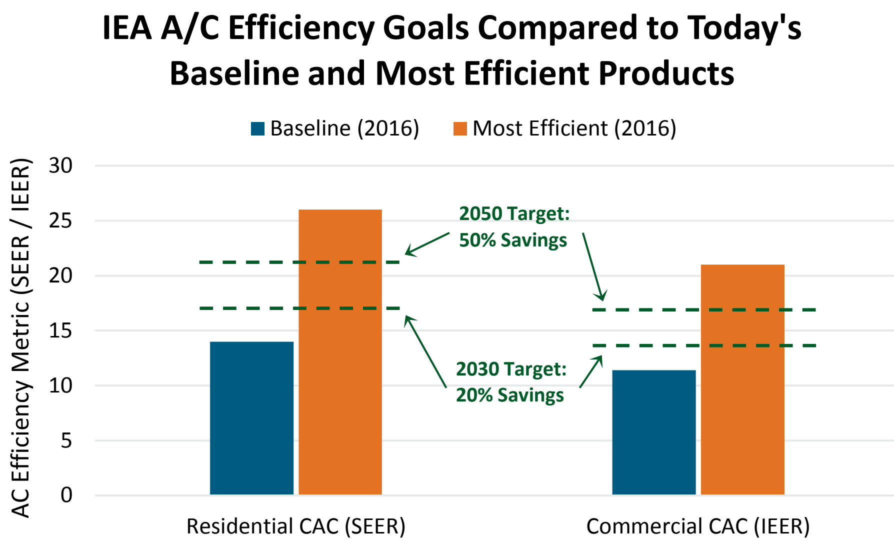
[94] Goetzler et al. 2013. "Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment." December 2013. Available at: http://energy.gov/sites/prod/files/2014/02/f8/Motor%20Energy%20Savings%20Potential%20Report%202013-12-4.pdf.
[95] Goetzler et al. 2015. "Pump and Fan Technology Characterization and R&D Assessment." October 2015. Available at: http://energy.gov/sites/prod/files/2015/10/f27/bto_pumpfan_report_oct2015.pdf.

5.3 Future Air Conditioning Efficiency Goals

Manufacturers and government R&D organizations continue to support advanced technologies that can further improve performance and reduce system costs. In a 2011 report, IEA researchers set a performance target for installed equipment of 20%-40% A/C efficiency improvement by 2030 and 30%-50% improvement by 2050 to reach global building energy-efficiency goals.[28] In June of 2016, the Clean Energy Ministerial (CEM) launched an Advanced Cooling Challenge with the support of the governments of the United States, India, China, Canada, and Saudi Arabia. The challenge aims to encourage the development and deployment of super-efficient, smart, climate-friendly, and affordable cooling technologies. Numerous manufacturers and non-profit groups have made commitments to support the challenge. Similar to the IEA report, the Clean Energy Ministerial challenge aims to improve average A/C system efficiency by 30% by 2030. This could reduce global CO_2 emissions by up to 25 billion metric tons over the lifetime of the equipment, which is equivalent to eliminating the annual emissions of 1,550 coal-fired power plants.[96]

As Figure 5-3 shows, select products on the market today can meet or exceed the Advanced Cooling Challenge efficiency targets for different A/C equipment types. While current technologies may provide high efficiency performance, the targets and products assume high-GWP HFC refrigerants, and the transition to low-GWP refrigerants may pose new challenges to match both baseline and high efficiency products. Nevertheless, laboratory testing (Section 4.2.2) has revealed several alternative refrigerants that provide similar or improved efficiency (COP) and capacity compared to the R-410A baseline with only soft-optimization. These initial results suggest that the A/C industry can meet or exceed these efficiency targets with A/C systems designed specifically for low-GWP refrigerants.

[96] "Clean Energy Ministerial Launches Advanced Cooling Challenge." 2016. Clean Energy Ministerial. Accessed June 3. http://www.cleanenergyministerial.org/News/clean-energy-ministerial-launches-advanced-cooling-challenge-68679.



Source: IEA (2011)[28], Lennox (2016)[97], Carrier (2016)[98]

Figure 5-3: IEA A/C efficiency goals compared to baseline and most efficient products[99]

While today's most efficient products already meet the EIA's performance targets, many of these high-efficiency technologies still have prohibitively high upfront costs for most of the global market. For example, the highest efficiency A/C products in the U.S. can carry an upfront cost premium of 50%-150% or greater, although this spread is gradually decreasing.[100] Consumers predominantly purchase baseline or moderate-efficiency equipment, so reducing the cost of high-efficiency products will continue to be a key research focus.

Along with performance goals, which reduce operating costs, the IEA also sets an equipment-cost reduction goal of 5-20% for high efficiency technologies. These lower-cost, high-efficiency systems will have a larger market impact through wider customer adoption and have the potential to drive new government appliance standards. For these reasons, the BTO emerging technology program sets cost reduction targets for various heat pump systems to "bend the cost curve" for high efficiency products and accelerate market adoption (See Table 5-2).

[97] Lennox XC25. Accessed April 2016. http://www.lennox.com/products/heating-cooling/air-conditioners/xc25

[98] Carrier WeatherExpert 48LC. Accessed April 2016. http://www.carrier.com/commercial/en/us/products/packaged-outdoor/outdoor-packaged-units/48lc/

[99] Performance estimates based on residential split-system A/C and commercial rooftop A/C products in US market. A/C equipment efficiencies (SEER, COP) are not directly comparable across equipment types or countries due to differing climate, technical specifications and test procedures.

[100] EIA. 2015. "Updated Buildings Sector Appliance and Equipment Costs and Efficiencies." U.S. Energy Information Administration. http://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf. Estimated price decreases reflect adjustments in DOE minimum efficiency standards and the availability of higher efficiency products.

Table 5-2: DOE BTO HVAC 2020 Cost Targets

Timeframe	Project Area	Metric	Building Type	Current Status (Best)	2020 Target	Cost Reduction (%)
Near-Term	Advanced vapor compression technologies[101]	Installed cost per kBtu/hr. in 2013$	Residential & commercial	$141.67	$82.90	41%
	Natural gas driven heat pumps[102]		Residential & commercial	$36	$57.90	n/a[a]
	Cold climate heat pumps[103]		Residential & commercial	$125.00	$59.00	52%
	Air-source integrated heat pump[104]	Installed cost per sq. ft.	Residential	Not on market	$3.32	n/a
	Multi-function natural gas driven heat pump[105]		Residential & commercial	$9.40	$3.40	64%
Long-Term	Non-vapor compression technologies[106]	Installed cost per kBtu/hr. in 2013$	Residential & commercial	Not on market	$80.30	n/a

Note a: Costs increase due to anticipated performance and efficiency improvements.

Source: DOE estimates based on EIA. (2015)[107]

5.4 Related A/C Emissions Reduction Strategies

Beyond transitioning to lower-GWP refrigerants (see Section 4) and improved A/C system efficiency, several additional strategies exist to reduce both direct and indirect emissions from A/C systems, including:

- **Refrigerant Management**: Low-charge, low-leak system designs as well as effective refrigerant management, particularly at end-of-life disposal, to reduce direct emissions

[101] EIA. (2015). Updated Buildings Sector Appliance and Equipment Costs and Efficiencies. Available online: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf Appliance Costs and Efficiencies, Residential Central AC (South), p.36, 2013 Typical (baseline cost/performance) and 2013 High ('Best' cost/performance)

[102] Ibid, Residential Gas-Fired Furnaces, p.23, 2013 Typical (baseline cost/performance) and 2013 High ('Best' cost/performance)

[103] Ibid, Residential Air Source Heat Pumps (heat mode), p.40, 2013 Typical (baseline cost/performance and 'Best' cost); ENERGY STAR, Most Efficient 2016 - Central Air Conditioners and Air Source Heat Pumps, Coleman Echelon Series 3 ton unit ('Best' performance)

[104] EIA, Appliance Costs and Efficiencies, combination of: Residential Electric Resistance Water Heaters, p.14; and Residential Air Source Heat Pumps (cool mode), p.40, 2013 Typical (baseline cost/performance); 'Best' figures based on expert assessment for commercial market

[105] Ibid, combination of: Residential Gas-Fired Water Heaters, p.9; Residential Gas-Fired Furnaces, p.23; and Residential Central AC (South), p.36, 2013 Typical (baseline cost/performance); no product on the market yet for 'Best' category

[106] Ibid, combination of: Residential Gas-Fired Water Heaters, p.9; Residential Gas-Fired Furnaces, p.23; and Residential Central AC (South), p.36, 2013 Typical (baseline cost/performance); no product on the market yet for 'Best' category

[107] EIA. (2015). Updated Buildings Sector Appliance and Equipment Costs and Efficiencies. Available online: https://www.eia.gov/analysis/studies/buildings/equipcosts/pdf/full.pdf.

- **High Performance Building Design**: Minimize the need for A/C use by reducing cooling loads
- **Renewable Energy**: Increasing the share of renewable electricity generation to reduce the carbon intensity of electricity used for A/C

5.4.1 Refrigerant Management

Reducing refrigerant emissions during operation, servicing, and end-of-life disposal can reduce both direct and indirect impacts. Many HVAC equipment types in developed countries have leakage rates of 10% per year or more during operation, due to limitations in joining techniques, system designs, and maintenance practices, all of which indicates significant opportunities for improvement.[108] This is especially true if routine system maintenance focuses on simply topping off refrigerant charge levels rather than active leak detection and prevention.

End-of-life refrigerant management in developing countries is a major source of refrigerant emissions because refrigerants in these countries are often deliberately vented to the atmosphere when the unit is scrapped. While many countries currently prohibit intentional venting of ODS, extending these prohibitions to all high-GWP refrigerant gases internationally could reduce CO_2-equivalent emissions substantially if implemented and successfully enforced.[109] Many developed nations, including the U.S., now prohibit the venting of HFCs.[110]

Beyond its direct climate impact, refrigerant leakage also adversely affects system efficiencies and cooling capacities, leading to potential increases in energy consumption. One study modeling the effect of refrigerant leakage on a 10.6 kW_{th} (3 ton) rooftop unit with a fixed orifice expansion device found that a 14% leakage reduced system capacity by 8% and efficiency by 5%.[111] Although thermostatic expansion valves can somewhat reduce these effects, refrigerant leakage nevertheless adversely affects A/C performance.

Adopting technology and policy best practices for refrigerant management can reduce leakage over the life of the system. Advances in joining technologies can reduce leakage during operation, especially as new heat exchanger designs increase the number of joints. Improved system sub-component design, tighter manufacturing tolerances, and improved installation practices can reduce leakage rates over time. Effective refrigerant management schemes include robust reporting and tracking requirements, as well as a system to induce recovery, recycling, reclamation, and ultimately, environmentally friendly destruction.[43] Reducing refrigerant leakage is particularly critical for flammable or toxic refrigerants (see Section 4).

[108] EPA. 2014. "Methodological Descriptions for Additional Source or Sink Categories: Annex 3." U.S. Environmental Protection Agency. https://www3.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Annex-3-Additional-Source-or-Sink-Categories.pdf.
[109] Navigant Consulting, Inc. 2016. "Review of Refrigerant Management Programs." AHRI Project 8018. Air Conditioning, Heating, and Refrigeration Institute. http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/Technical%20Results/AHRI_8018_Final_Report.pdf.
[110] EPA. 2016. "Stationary Refrigeration - Prohibition on Venting Refrigerants." Policies and Guidance. Accessed June 2016. Available at: https://www.epa.gov/section608/stationary-refrigeration-prohibition-venting-refrigerants.
[111] Breuker et al. 2000. "Smart Maintenance for Rooftop Units." ASHRAE Journal. November 2000. Available at: http://alpinems.com/pdfs/Smarter-Maintenance.pdf.

5.4.2 High Performance Building Design

While improving A/C efficiency reduces building energy consumption to satisfy the building's cooling load, high-performance building designs can reduce the overall cooling load itself. Building codes and performance standards such as ASHRAE 90.1[112] for commercial buildings and International Energy Conservation Code (IECC)[113] for residential buildings substantially reduce cooling demand and subsequent energy consumption relative to non-compliant buildings.

These standards use several methods to reduce cooling loads through waste-heat reduction and improvements to the building envelope, including walls, floors, roofs, and fenestrations (i.e., windows and doors). Reducing the heat transfer through the building envelope via conduction, radiation, and infiltration, in turn reduces the need for an A/C system to reject this heat from the conditioned space. Several building energy efficiency studies conducted in hot, humid climates found potential annual cooling load reductions of up to 38% from improved insulation alone, and up to 12% reductions from external shading.[114] In pilot projects, dynamic solar glazing reduced cooling loads by up to 20%.[115] Increasing the efficiency of lighting and other appliances that give off heat have the compound benefit of reducing cooling demand as well as direct energy consumption. Table 5-3 highlights several strategies to reduce space-cooling loads.[116]

Table 5-3: Cooling Load Reduction Options

Category	Technique	Description
Building Envelope (External)	Insulation	Increase thickness and/or R-value for walls, attics, etc. to reduce conduction heat gains
	Windows	Install multi-pane glass with inert gas fill and low-E coating to reduce U-factor. Dynamic glazing technology may further reduce solar heat gains by filtering out infrared radiation while continuing to provide natural lighting.
	Thermal Bridges	Eliminate gaps in building insulation that allow increased conduction through poorly resistive materials
	Roofing	Install light colored roofing to increase albedo and reduce solar heat gain. Vegetative roofs reduce roof temperatures through evapotranspiration[117]
	Surface Orientation	Design building layouts to avoid large sunlit exposures not shaded by vegetation or building outcroppings
	Infiltration/ Exfiltration	Minimize air exchange between conditioned space and outdoor environment while still providing adequate fresh air

[112] ASHRAE. 2013. "Standard 90.1." https://www.ashrae.org/resources--publications/bookstore/standard-90-1.
[113] International Code Council. 2012. "International Energy Conservation Code." http://publicecodes.cyberregs.com/icod/iecc/.
[114] Al-Tamimi, Nedhal Ahmed M., and Sharifah Fairuz Syed Fadzil. 2010., citing Bojic and Yik 2005; and Yang and Hwang 1995. "Evaluation on Cooling Energy Load with Varied Envelope Design for High-Rise Residential Buildings in Malaysia." In Proceedings of the Tenth International Conference for Enhanced Building Operations. Kuwait. Accessed May 2016. Available at: http://oaktrust.library.tamu.edu/bitstream/handle/1969.1/94126/ESL-IC-10-10-76.pdf?sequence=1.
[115] IEA. 2013. "Technology Roadmap: Energy Efficient Building Envelopes." https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyEfficientBuildingEnvelopes.pdf.
[116] In addition to more sustainable building designs, cooling energy demand can also be reduced by changing occupant behavior to allow comfort at higher thermostat set points, e.g., businesses allowing or encouraging their employees to wear lighter clothing in the summer. Swanson, Ana. 2015. "How America Fell in Love with Crazy Amounts of Air Conditioning." August 3, 2015. The Washington Post. Available at: https://www.washingtonpost.com/news/wonk/wp/2015/08/03/how-america-fell-in-love-with-crazy-amounts-of-air-conditioning/
[117] EPA. 2015. "Using Green Roofs to Reduce Heat Islands." Accessed April 2016. https://www.epa.gov/heat-islands/using-green-roofs-reduce-heat-islands.

Category	Technique	Description
Waste Heat Reduction (Internal)	Lighting	Install LED lighting with occupancy sensors to maintain lighting utility to building occupants while reducing waste heat
	Appliances	Install energy efficient appliances, especially major appliances that dispel heat within the building

5.4.3 Clean Energy

Incorporating renewable, low-carbon energy generation also reduces GHG emissions by lowering the carbon intensity of electricity generation, thereby reducing indirect emissions. A/C systems in particular present a unique opportunity for renewable energy integration as solar photovoltaics (PV) output coincides with peak daytime cooling demand. Nighttime wind generation can charge chilled-water thermal energy storage systems to provide on-peak demand reductions. While not currently in widespread use, thermally driven cooling systems (e.g., absorption, adsorption, desiccant) offer additional opportunities for renewable energy integration in the longer term (Section 7). Reducing the carbon intensity of utility-scale electricity generation through renewable or nuclear energy or through carbon capture and storage would reduce building-sector CO_2 emissions as well.[4,118]

[118] DOE. 2016. "Carbon Capture and Storage Research." http://energy.gov/fe/science-innovation/carbon-capture-and-storage-research

6 Cost of A/C Ownership

The industry can build on the lessons learned from the successful transition away from ozone-depleting refrigerants to mitigate the potential cost impacts of low-GWP A/C systems. Cost projections are still unclear for many of the low-GWP refrigerants and for the associated transitional engineering and capital investments. Nevertheless, the information available, including performance test results of alternative refrigerants, suggests that the cost to transition to low-GWP refrigerants is similarly manageable. Research organizations, government regulators, international bodies, and other stakeholders are collaborating to develop the technologies and policies necessary to minimize the uncertainty, risk, and burden on manufacturers and the cost impacts on consumers.

6.1 Potential Cost Concerns for Low-GWP Refrigerant Transition

The transition to low-GWP refrigerants requires special considerations to account for changes in refrigerant costs and for engineering and manufacturer re-tooling costs. Hydrocarbons and R-32, commonly proposed alternatives, are existing refrigerants (the latter as a component of R-410A), and so refrigerant costs are well established, as are the costs of many A/C components that are designed to use them. Costs for newer refrigerants, like HFOs, are less clear. As discussed in Section 4, above, most low-GWP refrigerants are not "drop-in" replacements and may have different operating characteristics than today's most common refrigerants. The industry expects these differences to increase A/C system cost, at least initially, due to the need for specialized component designs to account for different heat exchanger designs and operating pressures, or additional safety measures for those refrigerants that present flammability concerns. Each alternative refrigerant affects system costs differently and will have different solutions, for example:

- **HFOs:** Many low-GWP HFO refrigerants may have inherently higher costs than conventional refrigerants due to more complex manufacturing processes for these more complex molecules.[11] Although public cost estimates for low-GWP refrigerants for A/C applications are unavailable, some estimates exist for HFO refrigerants in other applications. One expert estimates the initial cost of R-1234yf (an HFO) for early adoption as a low-GWP replacement in mobile air conditioning could be as much as ten times the current cost of R-134a, before decreasing closer to 4 times or less after the market matures.[11,119,120] Another estimate suggests manufacture costs for R-1234yf may be 6-7 times higher than R-134a, but notes wide ranges in data sources and the opportunity for further cost reductions.[121] It is unclear how accurate or representative these cost estimates are for HFOs in general, especially in cases where the HFO is a

[119] Calm, James. 2012. "Refrigerant Transitions... Again." In ASHRAE/NIST Conference. Gaithersburg, MD. http://www.jamesmcalm.com/pubs/Calm%20JM,%202012.%20Refrigerant%20Transitions%20...%20Again.%20ASHRAE-NIST%20Refrigerants%20Conference.pdf. Calm estimates the 10-12x initial cost may reach 4-8x
[120] Cost projections for large-scale manufacturing of low-GWP refrigerants are not yet publicly available and these costs will vary between markets. With these uncertainties, estimating the cost impacts for low-GWP refrigerants in different markets is impossible to do in a realistic fashion before the industry provides their own detailed projections.
[121] UNEP. 2012. "Decision XXIII/9 Task Force Report: Additional Information on Alternatives to Ozone-Depleting Substances." Report of the Technology and Economic Assessment Panel. United Nations Environmental Programme. http://ozone.unep.org/Assessment_Panels/TEAP/Reports/TEAP_Reports/teap-task-force-XXIII-9-report-may2012.pdf. We used midpoints of price ranges in Tables 3-12 and 3-13.

component of a blend, which reduces the potential cost increases of pure HFO refrigerants because HFC components are less expensive than HFOs.

- **Existing alternative refrigerants:** Many non-fluorinated refrigerants (e.g., hydrocarbon, carbon dioxide) and existing low-GWP HFCs (e.g., R-32) have low costs. However, some of these refrigerants may introduce performance or safety issues that could reduce the cost advantage over new refrigerant options. For example, R-744 (CO_2) systems require more robust components to handle higher operating pressures and to compensate for performance degradation in high-ambient temperature environments. Systems using hydrocarbon refrigerants, such as R-290 (propane), require specialized components and safety measures to maintain safe operation with the flammable refrigerant. Nevertheless, manufacturers have developed certain refrigeration and A/C products that balance increased component cost with lower refrigerant cost and improved efficiency, which suggests these issues can be addressed in many applications.

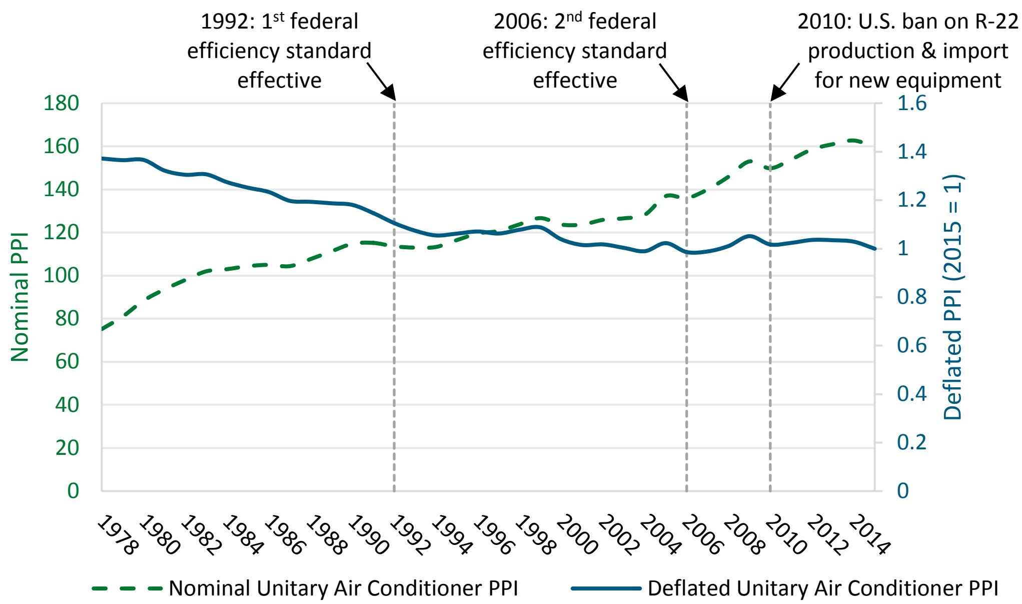
As production volumes increase and the market matures, the costs for A/C systems using low-GWP refrigerants are expected to decrease. As discussed in Section 6.2, the A/C industry has experience adapting to the initial cost increases during a refrigerant transition while still providing consumers with cost-effective products. The industry has multiple avenues to mitigate transition costs, including using components that use lower refrigerant charge (Section 6.3). Overall, the refrigerant itself remains a small portion of the total installed cost for most A/C systems (see Figure 6-2), despite the likely increase in costs relative to the HFC refrigerants being replaced.

6.2 Historical Refrigerant Transition Cost Impacts

Since the 1970s, U.S. manufacturers have reduced the inflation-adjusted cost of unitary A/C equipment, as Figure 6-1 shows for residential central ducted A/C systems (equipment costs only). This trend of decreasing costs has been concurrent with the ODS phase-out, as well as periodically increased efficiency standards. The reasons for this cost trend are complex, including technological innovations and manufacturing efficiencies, as well as macroeconomic factors related to globalization of manufacturing and commodity price trends. Consequently, future trends are difficult to predict.

During this transition away from ODS, U.S. manufacturers made one-time investments of an estimated $20M-$50M each to develop and test new products and reengineer their production facilities.[122] Unit production costs increased at least initially, primarily driven by the need for increased equipment robustness to accommodate R-410A's higher operating pressures. In the early 2000s, the higher cost HFC refrigerant itself increased production costs for U.S. manufacturers of residential ducted split-system A/C systems by $20-$30 per unit, not including the cost impacts of compressors, heat exchangers, controls, and other components designed for R-410A.[122] During this time, manufacturers continued to provide customers with A/C systems that achieved high performance and efficiencies, while maintaining cost effectiveness.

[122] 10 CFR Part 430. Federal Register/Vol. 67, No. 100/Thursday, May 23, 2002 EE-RM-STD-98-440 COMMENT 304



Sources: U.S. Bureau of Labor Statistics (2016),[123] Federal Reserve Bank of St. Louis (2016),[124] EPA. (2016),[125] ASAP (2016)[126]

Figure 6-1: Residential central A/C equipment costs from 1978 to 2015[127]

Both DOE's minimum efficiency standards and shipment-weighted efficiency improved substantially over this transition period (see Section 5), which decreased the life-cycle energy costs for equipment. These factors supported high volume sales and increasing market penetration for A/C systems in U.S. homes.[128] Research into historical A/C costs for other developed countries, such as Japan, echoes the U.S. trend.[129] Similar to the US, the reasons for these cost reductions in Japan are varied, and historical trends are not necessarily indicative of the future. However, having worked through refrigerant transitions previously, manufacturers understand the cost issues facing the low-GWP transition and are already developing solutions to deliver cost-effective, low-GWP A/C systems (see Section 4, above, and Section 7).

[123] U.S. Bureau of Labor Statistics. 2016. "BLS Series Report : U.S. Bureau of Labor Statistics." Accessed May 2016. Available at: http://data.bls.gov/cgi-bin/srgate.

[124] Federal Reserve Bank of St. Louis. 2016. "Gross Domestic Product: Chain-Type Price Index." FRED, Federal Reserve Bank of St. Louis. Accessed May 2016. Available at: https://research.stlouisfed.org/fred2/series/GDPCTPI/.

[125] U.S. EPA. 2016. "Phaseout of Class II Ozone-Depleting Substances." Policies and Guidance. Accessed May 2016. Available at: https://www.epa.gov/ods-phaseout/phaseout-class-ii-ozone-depleting-substances.

[126] Appliance Standard Awareness Project. 2016. "Central Air Conditioners and Heat Pumps." Accessed June 2016. Available at: http://www.standardsasap.org/product/central-air-conditioners-and-heat-pumps.

[127] Uses historical Producer Price Index (PPI) data for unitary air conditioner manufacturing from the U.S. Bureau of Labor Statistics (BLS). The price includes only equipment costs (i.e., excluding operating costs and installation costs). Product series ID: PCU333415333415E. PPI data is inflation adjusted by dividing the PPI series by the gross domestic product chained price index for the same years. Inflation adjusted PPI is normalized to 2015. While HCFC-22 was completely banned for use in new equipment in 2010, most U.S. manufacturers completed their transition from ODS well before this.

[128] U.S. EIA. 2011. "Air Conditioning in Nearly 100 Million U.S. Homes." August 19, 2011. Available at: https://www.eia.gov/consumption/residential/reports/2009/air-conditioning.cfm

[129] Shah, Nihar. 2016. "Leapfrogging to Super-efficiency and Low Global Warming Potential Refrigerants in Air Conditioning." May 17, 2016. Lawrence Berkeley National Laboratory. Presentation to Experts Group on R&D Priority-Setting and Evaluation. International Energy Agency. Available at: https://www.iea.org/media/workshops/2016/egrdspacecooling/5.NiharShah.pdf

6.3 Solutions to Mitigate Low-GWP Transition Costs

Operating costs constitute the majority of life-cycle ownership costs for A/C systems, so efficiency improvements can significantly reduce lifecycle costs (see Section 5). Nevertheless, consumers remain sensitive to upfront costs. In some cases, consumers may choose to repair rather than replace older equipment, thus extending the operating life of leaky, inefficient equipment. Manufacturers, policymakers, and other stakeholders, understanding the importance of initial costs to consumers, are pursuing several opportunities to help mitigate first-cost impacts during the transition to low-GWP A/C systems, including energy efficiency, charge reduction, system optimization, and supporting policies.

6.3.1 Lifecycle Costs and Energy Efficiency

Operating costs account for a majority share of lifecycle ownership costs for A/C systems,[130] especially for those systems installed in hot-humid climates.[131,132] Figure 6-2 shows the relative contribution of operating costs to a customer's total life cycle A/C costs in both the U.S. and India. For a hot-humid climate such as India, the A/C system's energy consumption can make up over 80% of a customer's lifecycle costs; this assumes a 7-year operating life, so for products with longer equipment lifetimes, the operating costs will constitute an even greater percentage of lifecycle costs. High operating costs provide incentive for consumers and policy makers to increase the energy efficiency of A/C systems.

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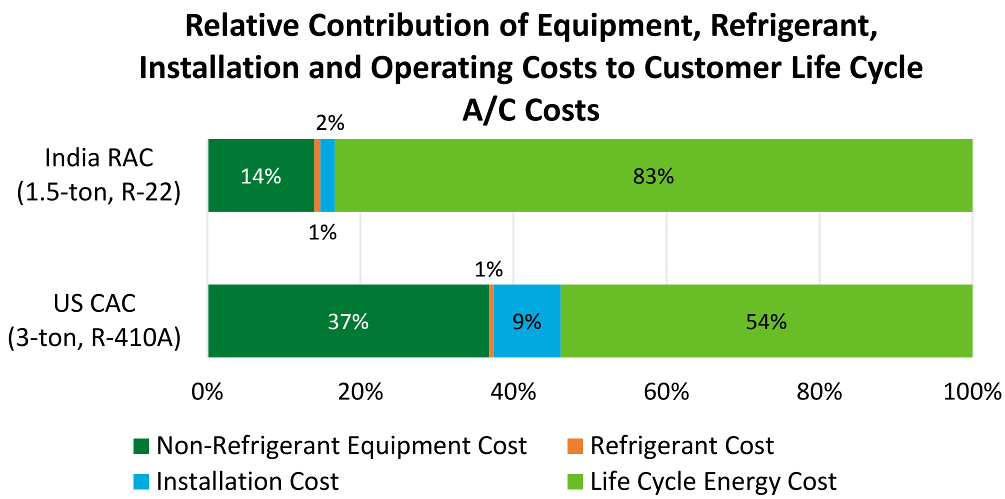
[130] Rosenquist et al. 2004. "Life-Cycle Cost and Payback Period Analysis for Commercial Unitary Air Conditioners." Lawrence Berkeley National Laboratory. March 2004. Available at: http://eetd.lbl.gov/sites/all/files/life-cycle_cost_and_payback_period_analysis_for_commercial_unitary_air_conditioners_lbnl-54244.pdf.
[131] ENERGY STAR Room A/C Calculator. Accessed April 2016. Available at: https://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/CalculatorConsumerRoomAC.xls
[132] ENERGY STAR Central A/C Calculator. Accessed April 2016. Available at: https://www.energystar.gov/ia/business/bulk_purchasing/bpsavings_calc/Calc_CAC.xls



Sources: U.S. CAC Technical Support Document (2015),[133] Shah et al. (2016),[134] Bhambure (2016)[135]

Figure 6-2: Residential life cycle A/C cost breakdown examples[136]

The lifetime-cost savings achieved with the use of higher-efficiency products may offset, in part or in full, the first-cost burden that consumers could see with low-GWP refrigerants. Several low-GWP alternatives identified in the Low-GWP AREP research program offer improved efficiency over typical HFC refrigerants (5-10% improvement, see Section 4) and manufacturers could incorporate a range of efficiency options (see Section 5) into optimized A/C systems while reengineering for alternative refrigerants. This approach provides manufacturers with the opportunity to provide products with lower total ownership costs while eliminating high-GWP refrigerants.

6.3.2 Charge Reduction

Reducing refrigerant charge can help mitigate the potential increased cost of low-GWP refrigerants, and may be a design requirement due to safety concerns. Incentives to reduce refrigerant charge have led the HVAC industry to innovate and develop more compact heat exchanger designs that maintain system efficiency and capacity. For example, moving from 3/8" (9.5 mm) to 7 mm tubes reduces charge by ~30% and a push to go to 5 mm tubes would provide a ~50% charge reduction. Microchannel heat exchangers are also becoming more prevalent, which promises significant charge reduction as well. As a result, new systems require lower quantities of refrigerant, thereby resulting in cost reductions.

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133 DOE. 2015. "Technical Support Document: Energy Efficiency Program for Consumer Products: Residential Central Air Conditioners and Heat Pumps." Regulations.gov. https://www.regulations.gov/#!documentDetail;D=EERE-2014-BT-STD-0048-0029.

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

135 Email correspondence with William Goetzler of Navigant Consulting, Inc. Bhambure, J M. 2016. "Installation Costs for Room Air Conditioners in India," May 25, 2016.

136 India RAC estimate based on Shah et al. (2016) estimates for equipment cost breakdown, markups, and average operating cost for a 7 year lifetime assuming 67.3 Rs to USD conversion. U.S. CAC estimate uses latest CAC TSD estimates of manufacture product cost (Table 5-14), markups (Table 6.8.1), and national average annual and discounted lifetime operating cost (Table 8.4.1) for a 3-ton split-system CAC including blower for a >20 year lifetime.

6.3.3 System Optimization

Most performance testing of low-GWP refrigerants, including the Low-GWP AREP research program and ORNL's High-Ambient-Temperature Testing Program (Section 4), only considered drop-in or soft-optimization scenarios. Manufacturers are already developing A/C systems using fully optimized designs and components. Performance of these systems will likely be better than the results obtained in drop-in and soft-optimization tests. Fully optimized systems can help mitigate, or even offset entirely, the higher cost of low-GWP refrigerants.

6.3.4 Supporting Policies

Governments and organizations can incentivize the transition to low-GWP refrigerants by developing policies that encourage adoption and mitigate manufacturer costs. For example, as parties to the Montreal Protocol phased out ODS, the Multilateral Fund made funding available to support developing countries through the transition. The EU and Japan have added a tax on HFC refrigerants ($26-$44/kg) to encourage the transition to low-GWP alternatives and to help fund this transition.[11] In addition, EU energy efficiency standards and labeling programs segment equipment into low-GWP and high-GWP classes, with high-GWP classes having higher efficiency standards and subsequent cost.[137]

6.4 A/C Industry Leadership through Low-GWP Refrigerant Transition

Manufacturers across the industry currently have the capabilities to develop and produce products using low-GWP refrigerants, and in many cases are already making good progress in these efforts. However, their efforts could be further accelerated through support and cooperation from research organizations, government regulators, international bodies, and other stakeholders. As Section 4 explains, the A/C industry has already taken proactive steps to understand and evaluate alternative refrigerants and committed to further laboratory research and product development. Efforts such as AHRI AREP provide an example of pre-competitive collaboration between various industry and research stakeholders to facilitate the transition to low-GWP refrigerants. While precise estimates of the investments required for the transition are unavailable, additional engineering costs will be required for each product line and market to develop, test, and manufacture low-GWP A/C systems, unless drop-ins are available. As evidenced by historical refrigerant transitions, the industry will invest the necessary technical and economic resources to overcome short-term challenges, and continue to deliver high-performing and cost-effective A/C systems. International efforts to standardize refrigerant regulations (Section 8) and share pre-competitive technical information (Section 4) can support the industry in cost-effectively adapting their current processes. Ultimately, these collaborative activities can minimize the uncertainty, risk, and burden on manufacturers, as well as any potential cost impacts on consumers.

[137] EU labeling for A/C systems. Accessed April 2016. http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32012R0206

7 Technology Outlook for Long-Term Options

New, entirely different A/C technologies are emerging. In addition to ensuring these new technologies are energy efficient, researchers are developing advanced vapor compression systems that use refrigerants with low-single-digit GWPs as well as non-vapor compression systems (e.g., solid-state or thermally activated cooling cycles) that avoid the need for refrigerants altogether. The long-term vision constantly evolves as researchers continue to redefine what is possible; however, the future is sure to include an innovative portfolio of technologies, whose advancement deviates from the path that A/C system development has historically followed.

7.1 Next-Generation A/C Technology Research Areas

Over the next several decades, A/C systems will transition to low-GWP refrigerants. In some markets and applications, systems may ultimately migrate to entirely different technologies that are both energy efficient and move beyond refrigerants altogether. Vapor-compression A/C systems have had broad adoption and success due to their scalability, relatively compact size, and high reliability; however, the challenges the industry faces today are motivating exploration of a broader array of technology solutions. Looking to the future, the next stage of A/C technology development will demonstrate the following:

- **Advanced Vapor-Compression Systems** –A/C technologies that significantly lower life cycle GWP and energy consumption for vapor-compression A/C systems while maintaining cost-competitiveness with today's high-volume equipment.
- **Emerging Non-Vapor-Compression (NVC) Systems** –A/C technologies that do not rely on refrigerant-based vapor-compression systems and can provide energy savings with high-volume cost similar to today's state-of-the-art.
- **Integration of A/C and Other Building Systems** –A/C technologies that share excess heat and other resources with other building systems to provide significant energy savings for the entire building.

The following sections discuss each of these technology categories, including example R&D projects supported by DOE[138] and other members of the IEA Heat Pump Centre.[139]

7.1.1 Advanced Vapor-Compression Systems

Today's vapor-compression A/C systems offer a wide range of efficiencies from baseline equipment with SEER/EERs in the low-to-mid teens, to the highest efficiency products in the mid-to-high 20s and beyond.[140] Vapor-compression A/C systems are expected to remain an important space cooling technology in the future, but will require R&D to introduce cost-effective, high-efficiency products using low-GWP refrigerants. Manufacturers already offer low-GWP A/C systems in select markets and equipment categories. These products closely match the performance and efficiency of today's baseline HFC systems, but further work is

[138] U.S. DOE BTO Emerging Technologies HVAC, Water Heating, and Appliances Program. Accessed May 2016. http://energy.gov/eere/buildings/hvac-water-heating-and-appliances
[139] IEA Heat Pump Centre. Accessed April 2016. http://www.heatpumpcentre.org/en/Sidor/default.aspx
[140] Range corresponds to baseline COPs of 3-4 and highest efficiency COPs of 6-7 and beyond.

needed to bring down the cost of baseline low-GWP systems, and then to develop low-GWP products offering efficiencies in line with today's best-in-class HFC equipment. Table 7-1 highlights several research projects to develop advanced vapor-compression A/C technologies using low-GWP refrigerants.

Table 7-1: Advanced Vapor-Compression Technologies under Development

Research Area	Description	Expected Commercialization Timeline
High-Performance Air Cycle Heat Pump	Developing a high-efficiency heat pump using air as the working fluid for space heating in commercial buildings.[141]	Medium-Term (2019-2023)
Low-GWP A/C System with Ultra-Small Centrifugal Compressor	Developing a centrifugal compressor using a low-GWP refrigerant to replace scroll compressors for light-commercial A/C systems[142]	Medium-Term (2019-2023)
High-Efficiency Low-GWP Compressor	Developing a high-efficiency compressor using a low-GWP refrigerant for residential and light-commercial A/C systems.[143]	Medium-Term (2019-2023)
Cold-Climate Heat Pumps	Developing residential and light-commercial heat pumps that provide high-efficiency space heating when operating in low ambient temperatures.[144,145,146]	Near-Term (2017-2019)
Commercial Gas-Engine Heat Pump	Developed and commercialized a gas-engine heat pump for commercial rooftop A/C applications. Note – this technology is currently available.[147]	Commercially Available

In addition to projects funded by research organizations, Section 4.3 highlights several manufacturer-led initiatives to develop advanced vapor-compression technologies using low-GWP refrigerants for different A/C applications, including:

[141] DOE. 2013. "Natural Refrigerant High-Performance Heat Pump for Commercial Applications." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/natural-refrigerant-high-performance-heat-pump-commercial-applications.
[142] DOE. 2015. "Low-Global Warming Potential HVAC System with Ultra-Small Centrifugal Compression." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/low-global-warming-potential-hvac-system-ultra-small-centrifugal.
[143] DOE. 2015. "High-Efficiency Low Global-Warming Potential (GWP) Compressor." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/high-efficiency-low-global-warming-potential-gwp-compressor.
[144] DOE. 2015. "High-Performance Commercial Cold Climate Heat Pump." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/high-performance-commercial-cold-climate-heat-pump.
[145] DOE. 2012. "Residential Cold Climate Heat Pump with Variable-Speed Technology." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/residential-cold-climate-heat-pump-variable-speed-technology.
[146] DOE. 2012. "Split-System Cold Climate Heat Pump." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/split-system-cold-climate-heat-pump.
[147] IntelliChoice Energy. Accessed April 2016. http://iceghp.com/gas-heat-pump/11-ton-gas-heat-pump/

- Small self-contained and mini-split A/Cs using R-32[148] and R-290[149]
- Residential and light-commercial PTACs using R-32[150]
- Commercial chiller systems using R-513A[151] and other refrigerants.

7.1.2 Emerging Non-Vapor-Compression Systems

Beyond low-GWP refrigerants, several alternative space-cooling technologies show potential to eliminate the direct CO_2 emissions of A/C systems. These NVC systems can provide sensible and/or latent cooling for buildings without the use of any refrigerants.

- Solid-state NVC technologies provide space cooling by using electrical energy to manipulate the intrinsic properties of solid-state materials (e.g., thermoelectric).
- Electro-mechanical NVC technologies use electrical energy to alter the phase or other properties of a working fluid (e.g., evaporative, thermoelastic),
- Caloric technologies exploit material properties that go through dramatic transformation under different types of excitation fields to provide cooling (magnetocaloric, electrocaloric, and elastocaloric)
- Thermally driven NVC technologies rely on thermal energy to drive mechanical or chemical cycles (e.g., absorption, desiccants).

Many NVC technologies are available today for specialized applications, but most require additional R&D to meet the cost, efficiency, and performance of vapor-compression A/C systems. For example, absorption chillers are an economical option when combined with a low cost heating source, and evaporative A/C systems are common in dry climates, but through additional R&D, researchers could reduce costs and expand their market opportunity. Several promising NVC technologies could someday provide high-efficiency space cooling with zero GWP working fluids (or no working fluid at all) and transform the traditional approaches for occupant cooling.[152,153] R&D efforts for NVC technologies focus on both material advances to improve the core of the NVC cooling system, and system integration strategies to transfer heat efficiently to/from the core material. Table 7-2 highlights several research projects to develop non-vapor-compression A/C technologies using solid-state materials and non-traditional materials.

[148] Cooling Post. 2014. "Advantage R290 and R32 in Battle for India." November 22, 2014. Available at: http://www.coolingpost.com/features/advantage-r290-and-r32-in-battle-for-india/
[149] Hydrocarbons 21. 2014. "R290 in Air Conditioning in China and India - Part I." September 10, 2014. Available at: http://www.hydrocarbons21.com/articles/5667/r290_in_air_conditioning_in_china_and_india-part_i
[150] Daikin. 2015. "White House Recognizes Air Conditioner and Chemical Manufacturer Daikin for Commitment to Reduce Greenhouse Gas Emissions." October 16, 2015. Available at: http://www.daikin.com/press/2015/151016/
[151] Chemours. 2016. "Opteon Refrigerants Increasingly Selected by Leading Global OEMs." January 25, 2016. Available at: https://www.chemours.com/Refrigerants/en_US/assets/downloads/opteon-refrigerants-selected-by-global-oems.pdf
[152] DOE ARPA-E. 2014. "Delta Program Overview." Accessed June 2016. Available at: http://arpa-e.energy.gov/sites/default/files/documents/files/DELTA_ProgramOverview.pdf.
[153] DOE ARPA E. 2014. "Delivering Efficient Local Thermal Amenities." http://arpa-e.energy.gov/sites/default/files/documents/files/MONITOR%20and%20DELTA%20Project%20Descriptions_Final_12.15.14.pdf

Table 7-2: Non-Vapor-Compression Technologies under Development

Non-Vapor-Compression Technologies	Description	Commercialization Timeline
Absorption / Adsorption	Sorption heat pumps use thermal energy (e.g., natural gas, solar) to drive the cyclical interaction between specialized working fluids or materials.[154] Note – commercially available for large capacity and specialty applications.	Near-Term (2017-2019)
Magnetocaloric	Magnetocaloric cooling systems provide space cooling by exposing specialized magnetocaloric materials to a strong magnetic field.[155,156]	Medium-Term (2019-2023)
Membrane	Membrane cooling systems provide space cooling and dehumidification by transferring moisture across specialized membranes using vacuum chambers.[157]	Medium-Term (2019-2023)
Electrochemical	Electrochemical compression uses specialized membranes and water working fluid to replace electrically driven mechanical compressors for A/C systems [158]	Medium-Term (2019-2023)
Elastocaloric	Elastocaloric cooling systems rely on stress and release that is applied to unique shape-memory alloys to provide space cooling.[159]	Long-Term (2023→)
Electrocaloric	Electrocaloric cooling system provides space cooling by applying an electrical field to a specialized electrocaloric material.[160]	Long-Term (2023→)

7.1.3 Integration of A/C with Other Building Systems

Beyond individual efficiency improvements, residential and commercial buildings can reduce their overall energy consumption by leveraging excess or waste energy from one building process to offset the consumption of another process. For example, a refrigerant-to-water heat exchanger can capture the heat rejected from an A/C condenser for water heating. Thermally driven heat pumps are another example where the excess heat from the gas burner could offset water heating energy consumption. In these cases, the building uses a higher percentage of the usable energy from the original source (e.g., natural gas burned on-site or at the electric power plant), which reduces the building's overall emissions. Several multi-functional building systems are on the market already, but integrated heat pumps in general require additional development

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[154] Annex 43. 2016. "Fuel Driven Sorption Heat Pumps." https://www.annex43.org/.
[155] Environmentally Low Impact Cooling Technology (ELICiT) Project. Accessed April 2016. http://elicit-project.eu/.
[156] DOE. 2016. "Novel Solid State Magnetocaloric Air Conditioner." http://energy.gov/eere/buildings/downloads/novel-solid-state-magnetocaloric-air-conditioner.
[157] DOE. 2016. "Membrane Based Air Conditioning." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/membrane-based-air-conditioning.
[158] DOE. 2016. "Low-Cost Electrochemical Compressor Utilizing Green Refrigerants for HVAC Applications." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/low-cost-electrochemical-compressor-utilizing-green-refrigerants-hvac.
[159] DOE. 2016. "Compact Thermoelastic Cooling System." Accessed June 2016. Available at: http://energy.gov/eere/buildings/downloads/compact-thermoelastic-cooling-system.
[160] DOE. 2016. "High Efficiency Solid-State Heat Pump Module." http://energy.gov/eere/buildings/downloads/high-efficiency-solid-state-heat-pump-module.

to reduce current cost premiums, advance prototypes into market-ready products, and incorporate low-GWP refrigerants. Table 7-3 highlights several research projects to develop A/C technologies that integrate with other building systems.

Table 7-3: Integrated A/C Technologies under Development

Research Area	Project Description	Commercialization Timeline
Ground-Source Integrated Heat Pump	A ground-source residential heat pump provides space cooling, space heating, and water heating. Note – this technology is currently available.[161]	Commercially Available
Heat Pump System for Cooling, Heating, Water Heating and Ventilation	A desuperheater is integrated with a heat pump system for service water heating, plus an energy recovery wheel for dehumidification.[162]	Near-Term (2017-2019)
Air-Source Integrated Heat Pump	An air-source residential heat pump provides space cooling, space heating, and water heating.[163]	Near-Term (2017-2019)
Solar Cooling & Heating using Solar PV or Solar Thermal Systems	Heat pumps produce cold/hot water or conditioned air through solar PV electricity, or solar thermal heat.[164]	Near-Term (2017-2019)
Combined Water Heater, Dehumidifier, and Cooler	An open absorption dehumidification system uses waste heat for water heating and condensed water for evaporative cooling.[165]	Medium-Term (2019-2023)
Natural Gas Boiler and CO_2 Heat Pump	A gas-fired boiler system drives a heat pump using CO_2 as the refrigerant for higher efficiency space and water heating.[166,167]	Medium-Term (2019-2023)
Natural Gas A/C and Heat Pump	A gas-fired residential heat pump provides space heating, space cooling, and water heating using the Vuilleumier cycle with helium working fluid.[168,169]	Medium-Term (2019-2023)
Multi-Function Gas-Fired Heat Pump	An engine-driven residential heat pump provides space cooling, space heating, water heating, and ancillary electrical power.[170]	Near-Term (2017-2019)

[161] ClimateMaster. 2015. "Trilogy 45 Geothermal Systems." March 2015. Available at: http://www.climatemaster.com/geothermal-dealer/wp-content/uploads/2015/05/RP943-ClimateMaster-Residential-Trilogy-45-Q-Mode-geothermal-heating-and-cooling-system-consumer-brochure.pdf

[162] Nagano, Katsunori. 2015. "Development of a Desiccant Ventilation System Using Wakkanai Siliceous Shale as Natural Meso-Porous Material." presented at the ICR 2015 Workshop, August 19. http://www.nedo.go.jp/content/100758020.pdf.

[163] http://energy.gov/eere/buildings/downloads/advanced-variable-speed-air-source-integrated-heat-pump-0

[164] IEA Solar Heating and Cooling Programme. 2016. "New Generation Solar Cooling & Heating Systems (PV or Solar Thermally Driven Systems)." http://task53.iea-shc.org/.

[165] http://energy.gov/eere/buildings/downloads/combined-water-heater-dehumidifier-and-cooler-whdc

[166] boostHEAT. Accessed April 2016. http://www.boostheat.com/en/

[167] IIR. 2015. International Institute of Refrigeration Newsletter. No. 63. July 2015. Available at: http://www.iifiir.org/userfiles/file/publications/newsletters/Newsletter_63.pdf

[168] DOE. 2016. "Natural Gas Heat Pump and Air Conditioner." http://energy.gov/eere/buildings/downloads/natural-gas-heat-pump-and-air-conditioner.

[169] DOE. 2015. "The Natural Gas Heat Pump and Air Conditioner." presented at the 2015 Building Technologies Office Peer Review. http://energy.gov/sites/prod/files/2015/05/f22/emt31_Schwartz_041415.pdf.

[170] DOE. 2016. "Multi-Function Fuel-Fired Heat Pump." Accessed June 7. http://energy.gov/eere/buildings/downloads/multi-function-fuel-fired-heat-pump-0.

7.2 Summary of A/C Research Needs

The many innovative A/C technologies and international R&D efforts underway show the potential for further improvements. Nevertheless, technical and market barriers limit the adoption of high efficiency products for much of the HVAC equipment market today. For example, less than a third of all central A/C systems purchased in the U.S. are SEER 15 or greater.[171] Reaching emissions goals will require the widespread adoption of cost-effective A/C systems that perform well-above current minimum efficiency standards.

Beyond the challenges of transitioning to low-GWP refrigerants (Section 4), Table 7-4 and Table 7-5 outline several technical and market barriers to the widespread adoption of high efficiency A/C systems and strategies to overcome these barriers. Governments and international organizations are continuing R&D support for promising A/C technologies to overcome these barriers, and are sharing technical findings and best practices through A/C industry conferences and collaborative research efforts, such as the IEA Heat Pump Centre.[172]

Table 7-4: Technical Barriers for High Efficiency A/C Technologies

Barrier	Strategy to Overcome Barrier
Climate-based Performance	System performance and efficiency vary based on outdoor temperatures, often rapidly decreasing for off-design conditions. Designs that manufacturers optimize for specific-climates (e.g., cold-climate, hot-dry, hot-humid), instead of traditional, one-size-fits-all-regions approaches, can reduce this barrier.
Variable-Capacity Performance	Contractors size A/C systems to meet design conditions during the hottest days of the year, but A/C systems often operate in conditions that are more moderate. Incorporating variable-speed components that enable variable-capacity performance can improve part-load performance.
Ventilation for Low-Infiltration Buildings	Traditionally, buildings receive ventilation air through operable windows or infiltration in cracks in the building envelope. To reduce space heating and cooling loads and prevent indoor contamination from poor outdoor air quality, high-performance buildings specify tight building envelopes, which creates the need for a separate mechanical ventilation system. In the future, manufacturers and contractors can incorporate ventilation strategies in A/C system designs, especially with window and ductless A/C products that do not use ducts.
Performance Persistence	As system complexity increases in order to achieve greater performance, degradation (fouling, mechanical wear, etc.) can have an outsized impact. Manufacturers are striving to design robust systems that maintain performance for the life of the product, alert the customer if maintenance is required, and diagnose the problem for the quick resolution by a contractor.

[171] Historical Energy Star Shipment data. Accessed April 2016 https://www.energystar.gov/index.cfm?c=partners.unit_shipment_data.
[172] IEA Heat Pump Centre. Accessed April 2016. http://www.heatpumpcentre.org/en/Sidor/default.aspx

Barrier	Strategy to Overcome Barrier
Communication with Demand-Side-Management Systems	Because most A/C systems use electrically driven compressors, increased A/C loads are a major driver of peak electric demand on the hottest days of the year. Demand-side-management strategies can offset these impacts by coordinating the control over a large number of A/C systems to cycle at alternating times or adjust thermostat temperatures slightly. Manufacturers, service providers, and utilities can encourage the adoption of these demand-response techniques by pre-installing communication equipment and incentivizing program adoption with up-front rebates and with time-of-use price incentives.

Table 7-5: Market Barriers for High Efficiency A/C Technologies

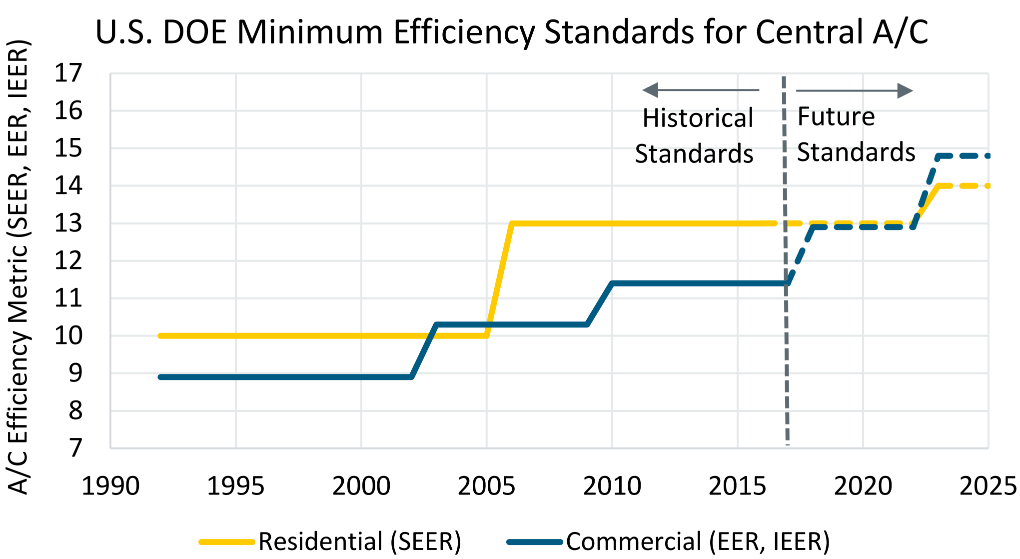
Barrier	Strategy to Overcome Barrier
Cost Effectiveness	First-costs and operating costs are key factors that influence market adoption for any major building system. First-cost is particularly important for A/C systems since it is typically a sizable investment for most home and building owners. Consumers who make purchase decisions based primarily on first cost will not be likely candidates for high-efficiency equipment that commands a cost premium, but saves on operating costs. This barrier is partially surmountable through greater consumer education and awareness of energy benefits, but first-cost barriers must also be addressed directly through innovative engineering and other methods.
Contractor Installation Practices	Many new HVAC products require additional resources and/or knowledge for safe, correct installation. Primary causes include heavier and larger equipment; system designs and architectures that are incompatible with existing building systems; or complex installation procedures that require specialized training and involvement of multiple trades. Without experience with these new products, installers in any market are hesitant to sell such systems.
Energy Efficiency in the Sales Process	New equipment purchases generally occur at the time of equipment failure and therefore consumers are limited to products that are readily available through their local distributor or HVAC contractor. They may not consider the lifetime energy savings from high efficiency equipment when they need to make a quick purchasing decision to replace failed equipment in the peak cooling season. In selecting new equipment, comfort, noise level, and other non-energy factors constitute the greatest influence on buying decisions. High efficiency equipment must incorporate these additional benefits in order to achieve substantial and rapid market adoption.

8 Regulatory Environment

Regulatory action at the national level, strengthened by international cooperation, has been successful at driving technology innovation and market adoption of both energy efficient A/C equipment and refrigerants with lower environmental impact, all at reasonable costs. The Montreal Protocol and related phase-out of ODS is an example of such international cooperation and enactment via domestic regulations. The implementation of high-GWP refrigerant phasedowns, effective refrigerant management, and energy efficiency policies by both developed and developing nations will be essential to reduce the global warming impact of future A/C demand growth.

8.1 Efficiency Standards

Developed nations, including the U.S., European Union nations, Australia, and Japan generally have minimum energy efficiency standards for A/C systems sold within their borders; such regulations have been effective in driving adoption of more energy efficient equipment. Figure 8-1 shows the progression of DOE minimum efficiency standards for residential and commercial A/C systems in the U.S. over time. This progression of increasing efficiency was concurrent with the phase-out of ozone-depleting refrigerants (see Section 8.2 below). Product labeling requirements often accompany minimum performance standards in order for consumers to more easily understand and compare the performance of different systems (See Section 5).



Source: DOE Appliance Standards Rulemaking Documents[173]

Figure 8-1: U.S. DOE A/C efficiency standards for major product categories

[173] Starting in 2015, DOE began applying higher efficiency standards to Southeastern and Southwestern states based on climate; these data are minimum national standards. For sources and details of regional differentiation for residential A/C equipment, see Figure 5-1. Projections for future residential A/C standards starting in 2023 are based on a term sheet produced from a negotiated rulemaking and is subject to further rulemaking. The term sheet is available at https://www.regulations.gov/#!documentDetail;D=EERE-2014-BT-STD-0048-0076. DOE expects to finalize its residential A/C standards by the end of 2016.

The adoption of energy efficiency standards by developing nations is less common than in developed nations, but is an effective method that some have begun to consider. For example, Ghana expects their energy efficiency standards for room air conditioners, implemented in the early 2000s, to avoid the need for up to 150 MW of electric generation capacity and reduce CO_2 emissions by approximately 2.8 million tons over 30 years.[174] However, Ghana's standards still have room for improvement; A/C systems installed in Japan, for example, still use half as much energy as those installed in Ghana, owing to much stricter Japanese minimum efficiency standards.[174] Developing nations should balance the effectiveness of stricter regulations with the added potential for cost-conscious consumers to find ways to avoid the regulations. The periodic review and update of energy efficiency standards can help maximize the cost-effective market adoption of high-efficiency options as they become available.

8.2 Montreal Protocol

Under the Montreal Protocol, Article 5 nations are given a longer phasedown window to minimize economic and energy impacts of the transition. With this longer phasedown schedule, the majority of new and existing air conditioners in Article 5 countries still use R-22.[175] In 2007, Parties to the Protocol agreed to an accelerated phase-out of HCFCs for Article 5 nations (see Table 8-1).[176] HFC refrigerants, which are the most common substitutes for CFCs and HCFCs, still have very high GWPs. Successfully agreeing on an approach to phase down HFCs will play a crucial role in meeting international goals as part of broader GHG emissions reduction strategies. International cooperation will be essential to achieving emissions reduction goals agreed to at the Paris Climate Conference at the end of 2015.

Table 8-1: Schedule for Article 5 Nations to Phase-Out Production and Consumption of HCFCs

Deadline	Reduction Step
By 2013:	Freeze HCFC consumption at base level (average of 2009-2010)
By 2015:	Reduction of HCFC consumption by 10%
By 2020:	Reduction of HCFC consumption by 35%
By 2025:	Reduction of HCFC consumption by 67.5%
By 2030:	Total phase-out (except as noted below)
2030-2040:	2.5% of baseline averaged over 10 years (2030-2040) allowed , if necessary, for servicing of refrigeration and A/C equipment existing as of January 1, 2030

Source: UNEP (2014)[19]

Commercial data for 1992, 2003 from: http://www.regulations.gov/#!documentDetail;D=EERE-2006-STD-0098-0033; 2005 data from: http://www.regulations.gov/#!documentDetail;D=EERE-2005-0002-0001; 2016 data from: http://www.regulations.gov/#!documentDetail;D=EERE-2013-BT-STD-0007-0113. Commercial efficiency standards switched from using the EER metric to the IEER metric to account for variable speed operation (i.e., part-load efficiency). DOE typically reviews its equipment standards every 6 years.

174 CLASP. 2016. "Success Story: Ghana." Accessed April 2016. http://clasp.ngo/en/OurPrograms/SuccessStories/Ghana.

175 UNEP RTOC (2014) estimates that approximately 50% of A/C units produced globally still use ODP refrigerants. With ODP phase out mostly completed in non-Article 5 countries, this means that a higher percentage of units currently produced in Article 5 countries still use ODP refrigerants.

176 UNEP. 2011. "HFCs: A Critical Link in Protecting Climate and the Ozone Layer." November 2011. Available at: http://www.unep.org/dewa/Portals/67/pdf/HFC_report.pdf

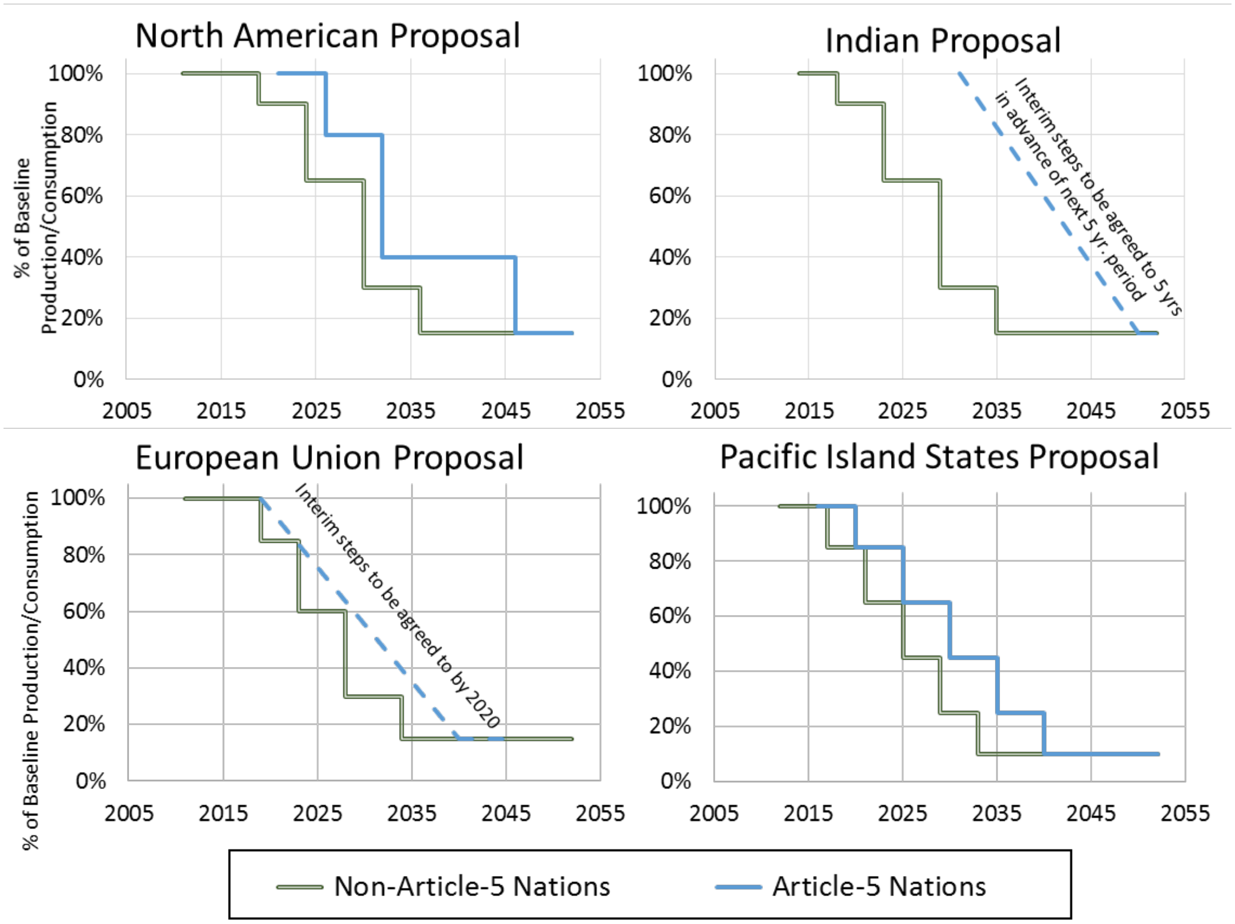
Independent of the accelerated HCFC phase out, four separate groups (North America,[177] the European Union, Pacific Island nations, [178] and India), each submitted proposed amendments to the Montreal Protocol in 2015 to reduce GWP-weighted HFC production and consumption incrementally over several decades. The four proposed amendments all seek to phase down GWP-weighted HFC production and consumption to 15% or less of "baseline" levels by 2050 (See Figure 8-2). All amendment proposals allow for delayed phase-down by Article-5 nations. Table 8-2 summarizes key provisions of each of the proposed amendments.

Table 8-2: Key Provisions of Montreal Protocol HFC Amendment Proposals

Proposal	Key Provisions
North America	• 85% phase-down of HFC production and consumption by 2046 for Article 5 nations and 2036 for Non-Article-5 nations
India	• 85% phase-down of HFC production and consumption by 2050 for Article 5 nations and 2035 for non-Article 5 nations • Interim phase-down steps for Article 5 nations to be agreed to 5 yrs. in advance of next 5 yr. period
European Union	• 85% phase-down of HFC production/consumption by 2034 for non-Article 5 nations; 85% phase-down of HFC/HCFC production by 2040 for Article-5 nations. • Freeze of combined HCFC and HFC consumption and HFC production in Article 5 nations by 2019 • Interim reduction steps for Article-5 nations to be agreed to by 2020
Pacific Island States	• 90% phasedown of production and consumption by 2040 for Article 5 nations and 2033 for non-Article-5 nations

Source: UNEP (2016)[179]

[177] Canada, United States, and Mexico
[178] Kiribati, Marshall Islands, Mauritius, Micronesia (Federated States of), Palau, Philippines, Samoa, and the Solomon Islands
[179] UNEP. 2015. "HFC Management Documents (From 2014 Onwards): Schematic summary of the HFC amendment proposals – corrected." United Nations Environmental Programme. http://ozone.unep.org/en/hfc-management-documents-2014-onwards.

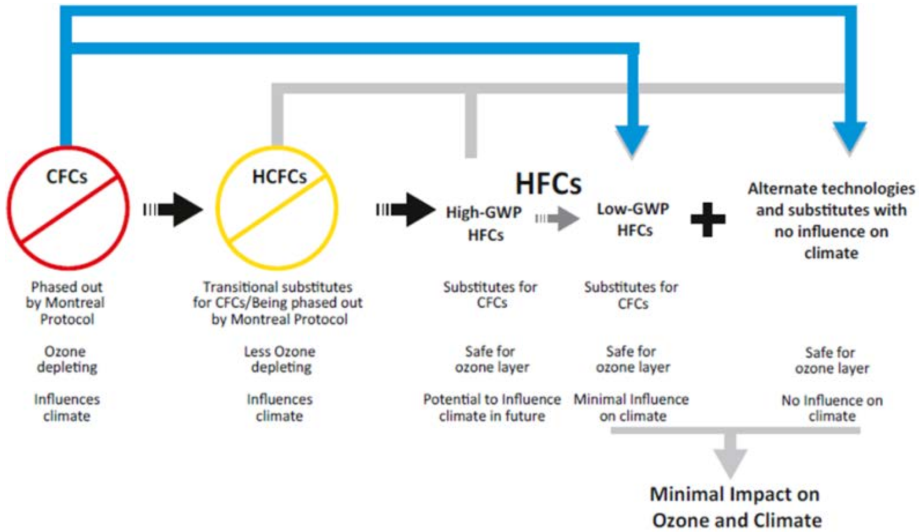


Source: UNEP HFC Management Documents (2015)[179]

Figure 8-2: Montreal Protocol amendment proposals

Any international amendment to phase out HFCs will accelerate the transition to low-GWP refrigerants for A/C systems more quickly than would be motivated by market forces alone. Such an agreement would avoid the need for some Article 5 nations to undergo a multi-step transition from today's HCFCs to high-GWP HFCs, and then to low-GWP A/C systems. Figure 8-3 highlights how a one-step transition to low-GWP refrigerants would "leapfrog" the high-GWP HFCs. In the medium-to-long term, viable technologies that have zero GWP will be developed, but going to low-GWP in the near-term likely reduces the overall cost and complexity for manufacturers, regulators, consumers, and other industry stakeholders.

The successful transition to non-ozone-depleting refrigerants under the Montreal Protocol occurred without unreasonably increasing the cost of A/C systems. The same policy framework can help build upon existing progress by individual nations in driving the global transition to climate-friendly alternative refrigerants. Strong energy efficiency and refrigerant policies for air conditioners fit within national goals of energy conservation and consumer protection, and will be required to meet international GHG emissions mitigation targets.



Source: UNEP (2011)[180]

Figure 8-3: Two-step and one-step "leapfrogging" refrigerant transition scenarios

While amendments to the Montreal Protocol are under negotiation, countries have been acting on their own to extend venting prohibitions and tracking provisions for ODS to include all fluorinated gases, and to phase down the highest GWP HFCs. For example, the U.S. banned HFC refrigerant venting in the early 2000's.[181] More recently, the European Union's 2014 "F-gas regulations" prohibit the sale, starting in 2020, of portable A/C equipment using any refrigerant with a GWP of 150 or more, as well as the sale of single-split A/C equipment using any refrigerant with a GWP of 750 or more. Efficiency standards for A/C in the European Union consider total climate impact and require slightly higher efficiency for equipment using refrigerants with GWPs higher than 150.[182] While the U.S. EPA has not banned any HFC refrigerants for air conditioning applications under SNAP, it did list several low-GWP acceptable alternatives for room air conditioners in 2015, including R-32, R-290 (propane), and the hydrocarbon blend R-441A.[183] The U.S. EPA has also proposed changing the status of certain high-GWP refrigerants for use in chillers to unacceptable beginning in 2024.[184] Australia and Japan have also implemented regulations to transition away from high-GWP refrigerants.

[180] UNEP. 2011. "HFCs: A Critical Link in Protecting Climate and the Ozone Layer." November 2011. Available at: http://www.unep.org/dewa/Portals/67/pdf/HFC_report.pdf
[181] EPA. 2016. "Stationary Refrigeration - Prohibition on Venting Refrigerants." Policies and Guidance. Accessed June 2016. Available at: https://www.epa.gov/section608/stationary-refrigeration-prohibition-venting-refrigerants.
[182] Regulation 517/2014 http://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2014.150.01.0195.01.ENG
[183] EPA SNAP Final Rules 19 and 20. http://www.epa.gov/snap/snap-regulations
[184] EPA. 2016. "Proposed Rule 21 Fact Sheet." https://www.epa.gov/sites/production/files/2016-03/documents/snap_action_factsheet.pdf.

9 Conclusions

In order to mitigate their climate impact, A/C systems of the future must minimize CO_2-equivalent refrigerant emissions and be energy-efficient. The long-term expectation involves a transition away from high-GWP refrigerants, combined with continuing trends of increased efficiency. For some applications, equipment will evolve using advanced vapor compression systems with significantly improved components to achieve high efficiency, while in other applications, manufacturers may incorporate entirely new technologies that eliminate the need for refrigerants altogether. This vision will not come about through market forces alone; accelerating climate change dictates that the global community drive global adoption of sustainable A/C systems using all available levers in order to achieve goals within targeted timeframes.

9.1 Current Landscape

With the backdrop of rising global average temperatures, increased frequency of deadly heat waves,[185] and improving standards of living in the developing world, air conditioning demand will increase significantly in the coming decades. Space-cooling energy consumption in developing nations alone may grow by 450% relative to 2010 levels as billions of people seek relief from high heat and humidity and the benefits of improved indoor air quality. Because A/C systems contribute to global GHG emissions both directly through refrigerant leakage and indirectly through fossil fuel combustion for electricity consumption, this anticipated demand growth could greatly increase GHG emissions if not addressed.

Common refrigerants in use today have GWPs thousands of times higher than carbon dioxide, so their leakage to the atmosphere has a disproportionate contribution to climate change compared to other GHGs. Researchers have identified alternative refrigerants with far lower GWPs and with comparable performance characteristics for most A/C applications. In testing, many low-GWP alternatives have shown the potential to match or exceed the efficiency of current refrigerants, which reduces both indirect emissions and operating costs. The industry is currently developing transition strategies to facilitate adoption of the top candidate alternatives. Because A/C units have long operating lifetimes, prompt initiation of this transition is important.

Industry and governments, having previously experienced a refrigerant transition, can apply many of the lessons learned to overcome the barriers that lie ahead. At this time, the exact magnitude of the potential cost impacts are unknown (for both the low-GWP refrigerant costs and the manufacturer re-tooling costs). However, upfront costs represent only part of the total cost of ownership for consumers; efficiency and operating cost improvements can help offset any first-cost increases. Additionally, international agreements can include financial and technical assistance provisions. During the phase-out of ODS under the Montreal Protocol, funding was made available for Article 5 (developing) nations to help local industries in reengineering their

[185] Committee on Extreme Weather Events and Climate Change; Board on Atmospheric Sciences and Climate; Division on Earth and Life Studies; National Academies of Sciences. 2016. "Attribution of Extreme Weather Events in the Context of Climate Change." National Academies of Sciences, Engineering, and Medicine. Accessed May 2016. Available at: http://www.nap.edu/catalog/21852/attribution-of-extreme-weather-events-in-the-context-of-climate-change.

products. Similar funding could be made available to aid developing nations as they transition to low-GWP refrigerants under an international HFC phasedown agreement.

The Montreal Protocol has proven to be a successful framework to address global environmental issues relating to refrigerants. The international community is seeking to build on the successful ODS phase out and extend the Montreal Protocol provisions to phase out high-GWP refrigerants. While these negotiations are pending, individual countries have taken steps to phase out the domestic use of high-GWP HFC refrigerants for end uses that have low-GWP alternatives available. Some manufacturers have already shown leadership through the introduction of low-GWP A/C products in a variety of markets and equipment types. Extending these policies and engineering efforts to the global audience is the critical next step in combating climate change through the reduction of high-GWP refrigerant production and consumption.

9.2 Pathway to the Future

The path to the future of A/C involves the development a cohesive set of solutions that are interdisciplinary and collaborative. Direct emissions reductions through a transition to low-GWP refrigerants are high-priority, as is the continued pursuit of cost effective efficiency improvements; however, industry leaders and other stakeholders pursuing these activities in concert with the other many available avenues will have the most success. Projected A/C growth in the coming decades, particularly in developing nations in hot climates, highlights the additional need to pursue cooling load reductions, waste heat recycling, and carbon-intensity reductions in electricity generation. Figure 9-1 highlights the key mechanisms for stakeholders to include in a comprehensive approach to meet global goals. Non-vapor compression technologies, at the intersection of energy efficiency and GWP reduction, provide potential value for both direct and indirect emissions reduction opportunities as one important piece of the long-term solution.

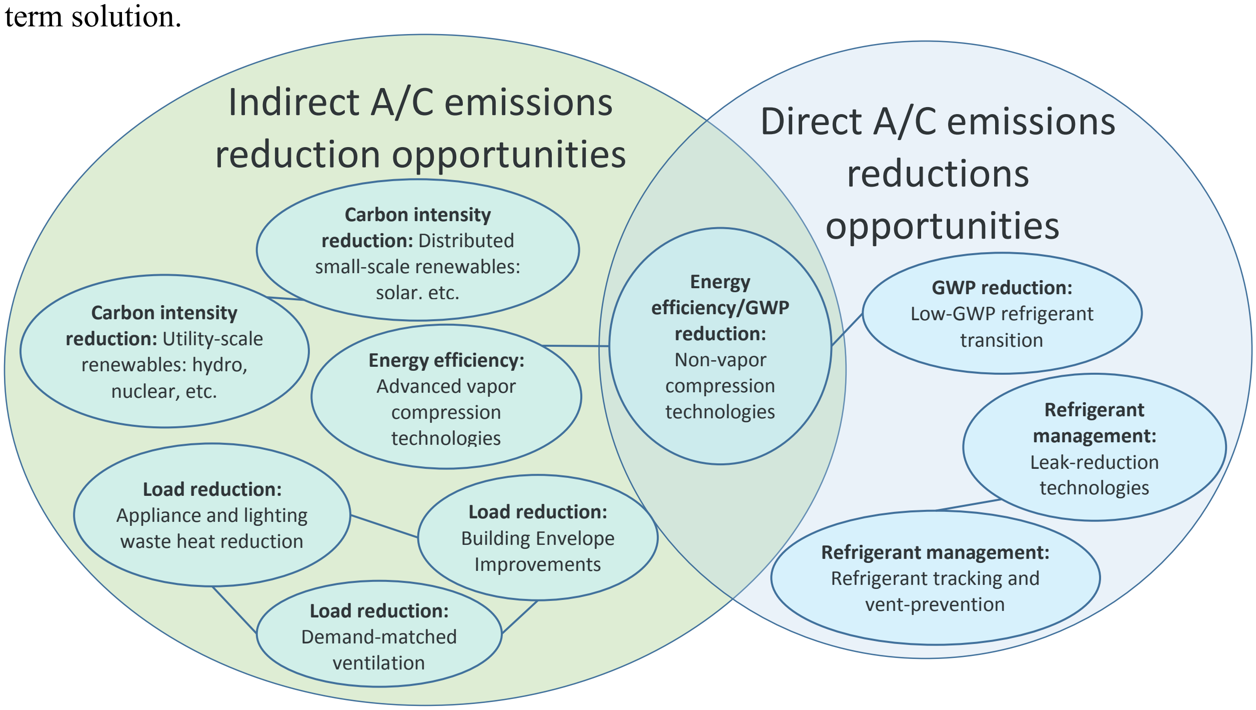


Figure 9-1: Elements of sustainable, low emissions building cooling systems

Prompt action to phase down the use of high-GWP refrigerants would significantly reduce future GHG emissions from A/C systems over a shorter timeframe than efficiency increases or other strategies alone could achieve. A transition to low-GWP refrigerants can occur in as short as a single turnover cycle of installed equipment. Low-GWP refrigerant deployment would additionally mitigate potential direct emissions growth in emerging markets that have limited refrigerant management programs. In these countries, end-of-life venting and other poor management practices could be common in the period before implementation of refrigerant management programs.

Ensuring the implementation of the solutions outlined in Figure 9-1 to reduce A/C-related emissions requires a comprehensive strategy based on international collaboration, domestic policy action, and R&D support from private and public sources (See Figure 9-2). Despite the numerous challenges, the A/C industry has successfully responded to international environmental issues through the phase-out of ODS refrigerants, and can assume a leading role in reducing global GHG emissions by transitioning A/C systems to use low-GWP refrigerants. Ultimately, success will require collaboration and active participation by a broad array of stakeholders.

Figure 9-2: Pathway to sustainable A/C future

The three key elements of a successful pathway include:

- **International Collaboration** – International cooperation is necessary to achieve this transition, such as increased research and development through Mission Innovation, or deployment activities through the Clean Energy Ministerial, i.e., the Advanced Cooling Challenge. Particular attention needs to be directed to high-ambient-temperature countries. Mission Innovation, launched at the 2015 Paris Climate Conference, is an international initiative to dramatically accelerate clean energy innovation by both the public and private sectors.[186] The investments stemming from Mission Innovation and its related activities will target both renewable energy and energy efficiency to drive global adoption of low-carbon electricity generation and high efficiency end-use equipment.

- **Domestic Policy and Regulation** – The adoption of any international agreement will require individual nations to phase down domestic usage of high-GWP refrigerants. Leading countries who have already started the low-GWP transition can provide example policies, strategies, and support to facilitate the phase-out process for other countries. The implementation of refrigerant policies that include robust refrigerant management schemes can minimize emissions of existing high-GWP refrigerant stocks during installation, maintenance, and end-of life reclamation. At the same time, the adoption and periodic strengthening of minimum efficiency standards by individual nations can ensure the adoption of cost-effective and high-efficiency A/C systems.
- **Emerging Technology R&D** – In addition to international and domestic regulatory activities, governments will achieve greater success by supporting R&D initiatives to develop, demonstrate, and deploy low-cost, safe, reliable, high-efficiency A/C equipment using low-GWP refrigerants or non-vapor-compression technologies. Beyond research into A/C technologies, projects focused on sustainable building design, renewable integration, and waste heat recycling can further reduce the GHG impacts of A/C systems. As these technologies are developed, higher-income nations may provide support to ensure their cost-effective adoption in developing countries.

The transition to a low-GWP future will not be immediate or easy for the A/C industry, but manufacturers have already begun developing alternatives and innovating to overcome the challenges posed by some of these alternatives. Promising new technologies are rapidly progressing from concepts to prototypes, offering additional opportunities for GHG emissions reductions in the longer term. Continued collaboration and support amongst the various international stakeholders will help ensure building occupants globally can realize the benefits of environmentally sustainable A/C systems.

[186] DOE. 2015. "Announcing Mission Innovation." http://www.energy.gov/articles/announcing-mission-innovation.

Appendix A: System Descriptions

This section contains brief profiles of A/C equipment types and system designs described in this report. These profiles provide summary information for a reader who is unfamiliar with certain A/C systems and are not intended to provide definitive descriptions or performance characteristics. The majority of information and figures are provided by a series of UNEP fact sheets on different HFC-consuming products prepared for an April 2015 Workshop on HFC Management.[187]

A.1 Packaged Room A/C (WRAC) and Portable A/C

Window and room air conditioners (WRAC) are primarily found in single and multi-family residential buildings in North America. Table A-1 provides key characteristics of WRACs and Figure A-1 highlights several system designs. This equipment category includes window, through-the-wall and portable air conditioners, as well as packaged terminal air conditioners, which are found in some residential high rise buildings. No ductwork is required and each unit is intended to cool a single room, so a dwelling may use multiple units.

Table A-1: Room A/C Equipment Summary

Characteristic	Value
Typical Refrigerant Charge	0.2 to 2.0 kg
Typical Cooling Duty	2 to 7 kW_{th} (0.5 to 2 tons)
Refrigerants	Current: R-410A, R-22, R-407C Alternative: R-290, R-32
Typical Location of Equipment	Located within the room and connects to exterior either through the window or through the wall
Typical Annual Leakage Rate	< 1%
Main Source of HFC Emissions	Losses at end-of-life and recovery
Approximate Split of Annual Refrigerant Demand	New equipment: 90%; Maintenance: 10%
Efficiency Range	9.0-11.0 Combined Energy Efficiency Ratio

Source: UNEP (2015)[188] includes PTACs, window A/C, and portable A/C units. Efficiency range from DOE Appliance Standards (2016)[189]

[187] UNEP Technical Issue Fact Sheets prepared for an April 2015 Workshop on HFC Management. Available at: http://ozone.unep.org/en/hfc-management-documents-2014-onwards

[188] UNEP. 2015. "Fact Sheet – Small Self-Contained Air Conditioning." Workshop on HFC Management Technical Issues. http://conf.montreal-protocol.org/meeting/workshops/hfc_management-02/presession/English/FS%207%20Small%20self%20contained%20air-conditioning%20final.pdf

[189] https://www.gpo.gov/fdsys/pkg/CFR-2012-title10-vol3/pdf/CFR-2012-title10-vol3-sec430-32.pdf, Accessed April 2016.

Source: UNEP (2015)[188]

Figure A-1: Window air conditioner

A.2 Ducted Split-System and Single-Package A/C

Single-family and smaller multi-family homes in North America commonly use ducted split-system air conditioners, also known as central air conditioners. Table A-2 provides key characteristics of residential ducted A/Cs and Figure A-2 highlights common system designs and components. These systems provide cooling by cycling refrigerant between an outdoor condenser and a central indoor evaporator coil, which return-air passes over before a fan circulates the air ducts throughout the conditioned space. In situations where limited indoor space exists, single-packaged A/Cs may sit outside the home and connect with internal ductwork (similar to commercial rooftop units).

Table A-2: Residential Ducted Split-System A/C Equipment Summary

Characteristic	Value
Typical Refrigerant Charge[43]	1.5 to 6.0 kg
Typical Cooling Duty	5.3 to 17.6 kW_{th} (1.5 to 5.0 tons)
Refrigerants	R-410A
Typical Location of Equipment	• Outdoor unit located next to exterior wall or roof • Indoor unit located in attic, basement, or utility closet and attached to duct system
Typical Annual Leakage Rate	12%
Main Source of HFC Emissions	Operating leakage
Efficiency Range	13-14 SEER baseline, and up to 26 SEER for high efficiency

Sources: DOE and ENERGY STAR minimum standards, product literature, efficiency range from DOE Appliance Standards (2016)[190], leakage from EPA (2015)[191]

[190] https://www.gpo.gov/fdsys/pkg/CFR-2012-title10-vol3/pdf/CFR-2012-title10-vol3-sec430-32.pdf, Accessed April 2016.
[191] EPA. 2015. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013." U.S. Environmental Protection Agency. EPA 430-R-15-004. April 15, 2015.

Source: EPA (2015)[192]

Figure A-2: Residential ducted central A/C (outdoor unit)

A.3 Ductless Split Systems

Ductless systems, also known as "mini-split" and "multi-split" systems, are manufactured primarily by Asian companies and are common in single and multi-family buildings globally with a relatively small but emerging market share in North America. Table A-3 provides key characteristics of residential ductless A/Cs and Figure A-3 highlights common system designs and components. These systems range in capacity from 1.75 – 21 kW_{th} (0.5 to 6 tons) and provide cooling by cycling refrigerant between an outdoor condensing unit and one or more indoor fan coil units that circulate room-air directly over an evaporator coil into the room. Systems with more than one indoor unit (i.e., multi-split systems) may use variable refrigerant flow (VRF) controls to regulate refrigerant flow to each zone to match more closely the cooling demand.

Table A-3: Ductless Split-System A/C Equipment Summary

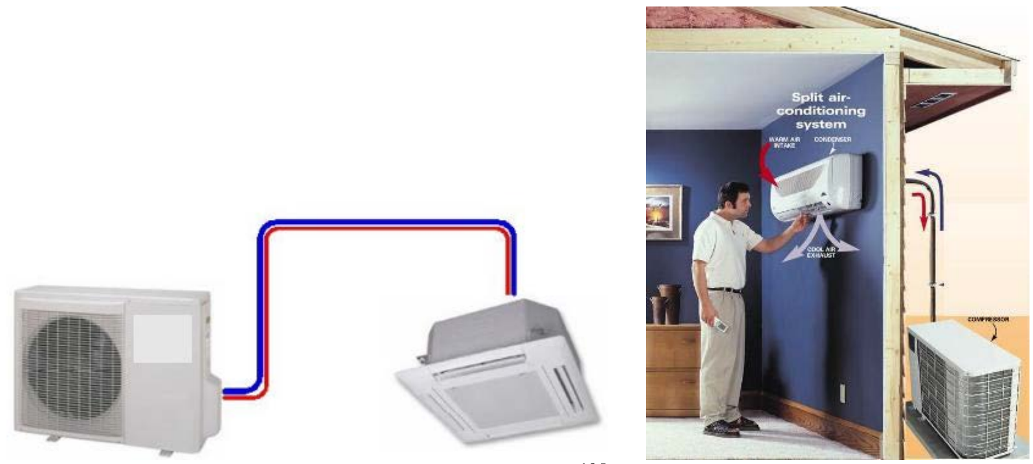
Characteristic	Value
Typical Refrigerant Charge	0.5 to 3.0 kg
Typical Cooling Duty	2 to 12 kW_{th} (0.5 to 3.4 tons)
Refrigerants	Current: R-22, R-407C, R-410A Alternative: R-32, R-290, R-1270
Typical Location of Equipment	• Indoor unit located within room • Outdoor units may be on the ground, balconies, or hung from the side of the building
Typical Annual Leakage Rate	1 to 4%
Main Source of HFC Emissions	Losses at end-of-life and recovery
Approximate Split of Annual Refrigerant Demand	New Equipment: 80% Maintenance: 20%
Efficiency Range	13-14 SEER baseline, and up to 25 SEER for high efficiency

Source: UNEP (2015)[193] Efficiency range from DOE Appliance Standards (2016)[194]

[192] EPA. 2015. "Transitioning to Low-GWP Alternatives in Residential & Light Commercial Air Conditioning." U.S. Environmental Protection Agency. September 2-2015. Available at: http://www.epa.gov/sites/production/files/2015-09/documents/epa_hfc_residential_light_commercial_ac.pdf

[193] UNEP. 2015. "Fact Sheet – Small Split Air Conditioning." Workshop on HFC Management Technical Issues. http://conf.montrealprotocol.org/meeting/workshops/hfc_management02/presession/English/FS%208%20Small%20split%20air-conditioning%20final.pdf

[194] https://www.gpo.gov/fdsys/pkg/CFR-2012-title10-vol3/pdf/CFR-2012-title10-vol3-sec430-32.pdf, Accessed April 2016.



Source: UNEP (2015)[195]

Figure A-3: Ductless mini-split system

A.4 Packaged Rooftop Unit A/Cs

Table A-4 provides key characteristics of packaged rooftop A/Cs and Figure A-4 highlights common system designs. The all-in-one system is located outside the building and connected to ductwork. Packaged rooftop units for light commercial applications typically have capacities between 18– 88 kW_{th} (5 and 25 tons), while larger units range in capacity from 263– 703 kW_{th} (75 to 150 tons).

Table A-4: Commercial Packaged Rooftop A/C Equipment Summary

Characteristic	Value
Typical Refrigerant Charge	5-10 kg for 12-20 kW_{th} (3 to 6 RT) light commercial system
Typical Cooling Duty	Light commercial: 18– 88 kW_{th} (5 and 25 tons) Large commercial: 263– 703 kW_{th} (75 to 150 tons)
Refrigerants	R-410A, R-407C
Typical Location of Equipment	Located on building roof and attached to duct system
Typical Annual Leakage Rate	2-6%
Main Source of HFC Emissions	Operating leakage
Approximate Split of Annual Refrigerant Demand	New Equipment: 50% Maintenance: 50%
Efficiency Range	9.8-11.2 EER (current standard), 11.4-12.9 IEER (standard in 2018), with products available up to 21 IEER

[195] UNEP. 2015. "Fact Sheet – Small Split Air Conditioning." Workshop on HFC Management Technical Issues. http://conf.montrealprotocol.org/meeting/workshops/hfc_management02/presession/English/FS%208%20Small%20split%20air-conditioning%20final.pdf

Source: UNEP (2015)[196], efficiency range from DOE Appliance Standards (2016)[197]

Source: UNEP (2015)[196]

Figure A-4: Commercial packaged rooftop air conditioner

A.5 Commercial Ductless A/Cs

Similar to residential ductless models, ductless commercial A/C systems are manufactured primarily by Asian companies and are popular in global markets, but only recently introduced in North America. Table A-5 provides key characteristics of commercial ductless and VRF A/C systems and Figure A-5 highlights common system designs. Most commercial ductless systems feature variable refrigerant flow controls, which increase refrigerant flow to zones with higher cooling demand and reduce flow to zones with lower demand.

Table A-5: Ductless Multi-Split A/C Equipment Summary

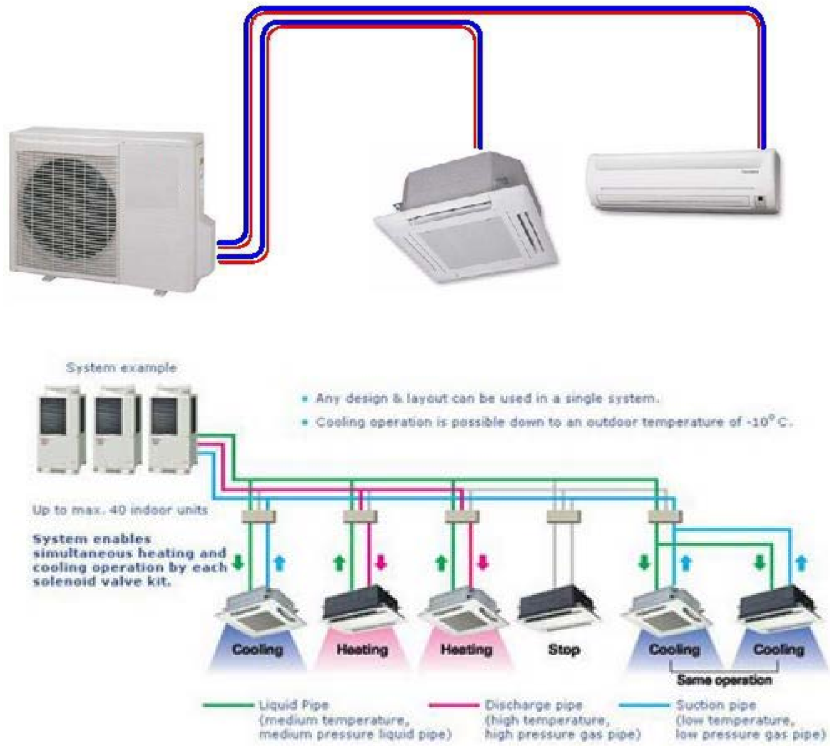
Characteristic	Large Single-Split / Multi-Split Systems	VRF Systems
Typical Refrigerant Charge	3-10 kg	5-100 kg
Typical Cooling Duty	10-40 kW_{th} (3 to 11 tons)	12-150 kW_{th} (3 to 43 RT)
Refrigerants	Current: R-410A, R407C Alternative: R-32, others	
Typical Location of Equipment	• Outdoor unit located next to exterior wall or roof • Indoor unit located within room or ceiling	
Typical Annual Leakage Rate	1-4%	1-5%
Main Source of HFC Emissions	Losses at end-of-life and recovery	

[196] UNEP. 2015. "Fact Sheet – Large Air Conditioning (Air-to-Air)." Workshop on HFC Management Technical Issues. http://conf.montreal-protocol.org/meeting/workshops/hfc_management-02/presession/English/FS%209%20Large%20air%20to%20air%20air-conditioning%20final.pdf

[197] Appliance and Equipment Standards Rulemakings and Notices Webpage for Small, Large, and Very Large Commercial Package Air Conditioners and Heat Pumps. https://www1.eere.energy.gov/buildings/appliance_standards/standards.aspx?productid=35 Accessed April 2016.

Characteristic	Large Single-Split / Multi-Split Systems	VRF Systems
Approximate Split of Annual Refrigerant Demand	New Equipment: 75% Maintenance: 25%	New Equipment: 65% Maintenance: 35%
Efficiency Range	9.8-11.2 EER	

Source: UNEP (2015)[198], efficiency range from DOE Appliance Standards (2016)[199]



Source: UNEP (2015)[198]

Figure A-5: Ductless multi-split system with VRF

A.6 Chillers

Larger commercial buildings and district cooling systems use hydronic chiller systems to provide cooling. Table A-6 provides key characteristics of different commercial chiller classes and Figure A-6 highlights common system designs. Chillers typically utilize an electrically driven vapor compression cycle to provide chilled water, which pumps distribute via a piping loop to air handlers, distributed fan coils, or radiant panels throughout the building. The system rejects heat to the ambient environment via refrigerant-to-air condensers, or refrigerant-to-water cooling

[198] UNEP. 2015. "Fact Sheet – Large Air Conditioning (Air-to-Air)." Workshop on HFC Management Technical Issues. http://conf.montreal-protocol.org/meeting/workshops/hfc_management-02/presession/English/FS%209%20Large%20air%20to%20air%20air-conditioning%20final.pdf

[199] https://www.gpo.gov/fdsys/pkg/CFR-2012-title10-vol3/pdf/CFR-2012-title10-vol3-sec430-32.pdf, CFR 431.97 Energy Efficiency Standards and their Compliance Dates. Available at: http://www.ecfr.gov/cgi-bin/text-idx?SID=a69096e892b13c204bbe6da3a92f8111&mc=true&node=se10.3.431_197&rgn=div8 Accessed April 2016, Accessed April 2016.

towers. Chiller systems have a wide capacity range from 176 – 8,792 kW_{th} (50 up to 2,500 tons) or more, with some units capable of reverse operation as heat pumps. The capacity requirement for chillers influences both compressor type (reciprocating, scroll, screw, or centrifugal) as well as refrigerant choice.

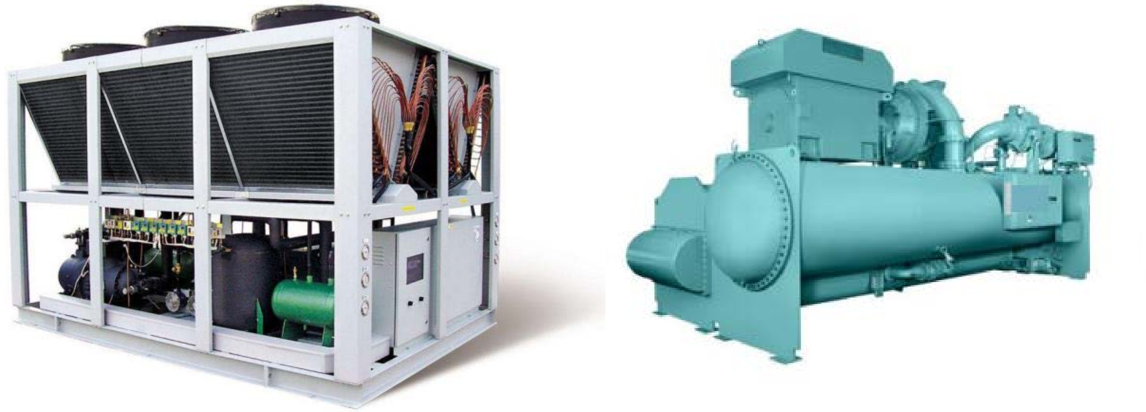
Table A-6: Chiller Equipment Summary

Characteristic	Small / Medium Chillers	Large Chillers
Typical Refrigerant Charge	40-500 kg	500-13,000 kg
Typical Cooling Duty	50 to 750 kW_{th} (14 to 213 tons)	750 to 10,000 kW_{th} (213 to 2,843 tons)
Refrigerants	Current: R-407C, R-410A Alternative: R-32, R-290, R-452B	Current: R-134a, R-123 Alternative: R-1234yf, R-1234z(E), R-513A, R-514A, and R-1336mzz(Z)
Refrigeration Circuit	• DX evaporator, air cooled condenser • Scroll, reciprocating or small screw compressor	• Flooded evaporator, water cooled condenser • Large screw or centrifugal compressor
Typical Location of Equipment	Machinery room (water-cooled) or outdoors (air-cooled)	
Typical Annual Leakage Rate	2-4%	
Main Source of HFC Emissions	Operating leakage	
Approximate Split of Annual Refrigerant Demand	New systems: 65%, Maintenance: 35%	New systems: 50%, Maintenance: 50%
Efficiency Range	• Air-cooled: 9.7-10.1 EER, 13.7-16.1 integrated part-load value (IPLV) • Water-cooled, positive-displacement: 0.56-0.78 kW/ton, 0.38-0.60 IPLV • Water-cooled, positive-displacement: 0.560-0.695 full load (FL), 0.380-0.550 IPLV	

Source: UNEP (2015)[200] Trane (2015)[201]

[200] UNEP. 2015. "Fact Sheet – Water Chillers for Air Conditioning." Workshop on HFC Management Technical Issues. http://conf.montrealprotocol.org/meeting/workshops/hfc_management02/presession/English/FS%2010%20Water%20chiller%20for%20air-conditioning%20final.pdf

[201] Trane. 2015. "Engineers Newsletters – ASHRAE Standard 90.1-2013 HVAC and Power Section Highlights." March 2015. Available at: https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/education-training/engineers-newsletters/standards-codes/ADMAPN053EN_0315.pdf



Source: UNEP (2015)[202]
Figure A-6: Centrifugal commercial chiller system

A.7 Other Commercial Equipment

Packaged Terminal Air Conditioners

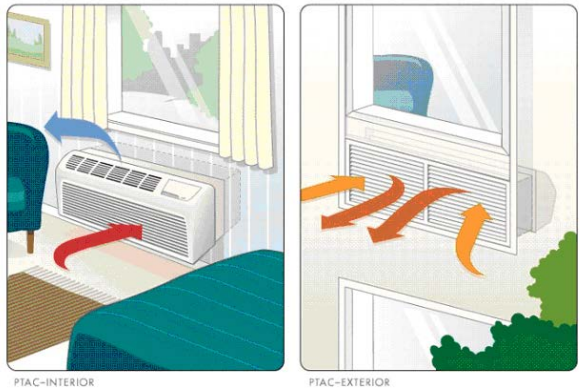
Packaged terminal A/C (PTAC) and packaged terminal heat pumps (PTHP) are similar to residential room A/C systems and are installed through walls with the evaporator facing indoors and the condenser facing outdoors. Table A-7 provides key characteristics of PTACs and Figure A-7 highlights common system designs. Hotels and offices are the primary users of PTAC/PTHP, as well as some high-rise residential buildings in North America. They range in capacity from 1.75 – 10.5 kW_{th} (0.5 to 3 tons) and can only serve limited areas, so multiple units may serve large rooms.

Table A-7: Packaged Terminal A/C Equipment Summary

Characteristic	Value
Typical Refrigerant Charge	0.5-1.0 kg
Typical Cooling Duty	2.0 to 4.4 kW_{th} (0.5 to 1.25 tons)
Refrigerants	Current: R-410A, R-22 Alternatives: R-32, R-290, R-441A and R-452B
Typical Location of Equipment	Located within the room and connects to exterior through the wall
Typical Annual Leakage Rate	4%
Main Source of HFC Emissions	Operating leakage
Efficiency Range	9.3-11.7 EER (2016), 9.5-11.9 (2017)

Source: EPA (2015)[203], DOE Appliance Standards (2015)[204,205]

[202] UNEP. 2015. "Fact Sheet – Water Chillers for Air Conditioning." Workshop on HFC Management Technical Issues. http://conf.montrealprotocol.org/meeting/workshops/hfc_management02/presession/English/FS%2010%20Water%20chiller%20for%20air-conditioning%20final.pdf
[203] EPA. 2015. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2013." U.S. Environmental Protection Agency. EPA 430-R-15-004. April 15, 2015.
[204] CFR 431.97 Energy Efficiency Standards and their Compliance Dates. Available at: http://www.ecfr.gov/cgi-bin/text-idx?SID=a69096e892b13c204bbe6da3a92f8111&mc=true&node=se10.3.431_197&rgn=div8 Accessed April 2016
[205] 201506 Final Rule: Technical Support Document: Energy Efficiency Program for Commercial and Industrial Equipment: Packaged Terminal Air Conditioners and Heat Pumps. Accessed April 2016. Available at: https://www.regulations.gov/#!documentDetail;D=EERE-2012-BT-STD-0029-0040

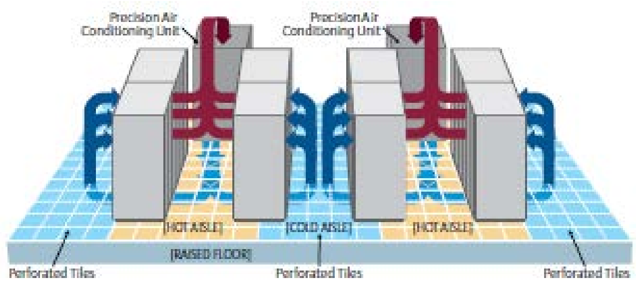


Source: UNEP, 2015[206]

Figure A-7: Packaged terminal air conditioner

Computer Room Air Conditioner

Computer room air conditioners (CRACs) are split-system air conditioners designed for precise temperature and humidity control for server racks. Figure A-8 provides an example system design. Typically, computer room air conditioners circulate cooled air through server racks using underfloor or overhead ducts. For larger IT facilities, such as data centers, centralized chillers supply a larger number of CRACs. Server cooling constitutes a large portion of data center energy demand, and can reach 50% of total site consumption.[207]



Source: Emerson[208]

Figure A-8: Computer room air conditioner

[206] UNEP. 2015. "Fact Sheet – Self-Contained Air Conditioning." Workshop on HFC Management Technical Issues. http://conf.montreal-protocol.org/meeting/workshops/hfc_management02/presession/English/FS%207%20Small%20self%20contained%20airconditioning%20final.pdf

[207]Rocky Mountain Institute, 2012. "Making Big Cuts in Data Center Energy Use" http://blog.rmi.org/blog_making_big_cuts_in_data_center_energy_use

[208] Emerson Network Power. 2007. "Five Strategies for Cutting Data Center Energy Costs Through Enhanced Cooling Efficiency." Available at: http://www.emersonnetworkpower.com/documentation/en-us/brands/liebert/documents/white%20papers/data-center-energy-efficiency_151-47.pdf

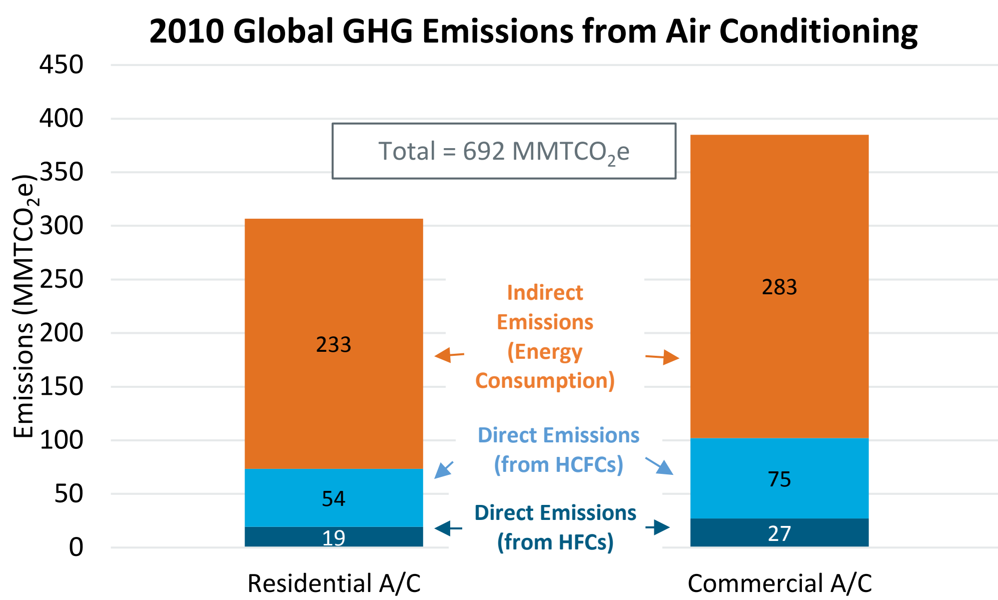
Appendix B: Methodology to Estimate Greenhouse Gas Emissions from A/C Systems

General Methodology

Estimations of direct and indirect impacts are subject to significant uncertainty and depend heavily upon assumptions regarding annual and end-of-life refrigerant leakage rates, climate, system type, and electricity generation mix. This appendix provides the detailed methodology and assumptions used in developing estimates for direct and indirect greenhouse gas emissions attributable to A/C systems, reported in Section 3:

- **Direct emissions** occur when refrigerant escapes from the A/C system into the atmosphere during initial charging, servicing, end-of-life disposal, and other events. Direct emissions are estimated by multiplying the mass of refrigerant released by its global warming potential (GWP). For this analysis, HCFC and HFC emissions are estimated separately using different methodologies; HFC emissions are estimated using a "bottom-up" approach, while HCFC emissions are estimated using a "top-down" approach.
- **Indirect emissions** result from fossil fuel combustion to generate electricity to operate the A/C system. Indirect emissions are estimated by multiplying the global energy consumption for space cooling by an emissions factor (i.e., the amount of carbon dioxide emitted to generate a given amount of electricity).

Figure B-1 summarizes annual global direct and indirect CO_2-equivalent emissions for residential and commercial A/C systems in 2010. The final GHG emissions values used in Section 3 and specifically Figure 3-2 (duplicated in Figure B-1) are bolded and underlined.



Sources: IPCC (2014),[32] World Bank (2014),[209] EPA (2012),[210] Xiang, et al. (2014),[211] ICF (2007)[212]

Figure B-1: Estimated global GHG emissions from air-conditioning systems in 2010

B.1 Indirect Emissions Estimates

Climate Change 2014: Mitigation of Climate Change, published by the IPCC, reports global site energy consumption for both residential and commercial buildings and breaks down these values by various applications, including space cooling. Table B-1 details the derivation of space cooling energy consumption (kWh) by sector using the following equation:

$$\boldsymbol{Q_{cooling}}(kWh) = \boldsymbol{Q_{total}}\,(PWh)x\,\boldsymbol{P_{cooling}}(\%)\;x\;\frac{\mathbf{10^{12}}\boldsymbol{kWh}}{\mathbf{1}\,\boldsymbol{PWh}}$$

$\boldsymbol{Q_{cooling}}$ = Global cooling energy consumption of residential or commercial buildings
$\boldsymbol{Q_{total}}$ = Total global energy consumption for residential or commercial buildings
$\boldsymbol{P_{cooling}}$ = Proportion of total residential or commercial building energy consumption attributable to space cooling

Table B-1: Space Cooling Energy Consumption Estimates

Sector	2010 Total Site Energy Consumption (PWh)[1]	Percentage for Space Cooling	Cooling Site Energy Consumption (kWh)
Commercial	8.42	7%	***5.89 x 10¹¹***
Residential	24.3	2%	***4.86 x 10¹¹***

Source: Figure 9.4 in IPCC (2014)[32]

The cooling energy consumption values correspond to indirect emissions through an emissions factor. The emissions factor corresponds to the global average mass of CO_2 emitted to produce each kWh of site electricity.

The World Bank reports a range for this global emissions factor between 460 and 500 g CO_2/kWh. We use the median value of this range for this analysis, 480 g CO_2/kWh. Table B-2 reports the derivation of indirect CO_2 emissions (million metric tons [MMT]) using the following equation:

$$\boldsymbol{E_{indirect}}(MMt\ CO_2) = \boldsymbol{Q_{cooling}}(kWh)x\ \boldsymbol{EF}\left(\frac{g\ CO_2}{kWh}\right)x\ \frac{\mathbf{1\ MMt}}{\mathbf{10^{12}g}}$$

$E_{indirect}$ = Global indirect CO_2 emissions from A/C systems
EF = Emissions factor (480 g CO_2/kWh)

Table B-2: 2010 Global Indirect GHG Emissions for Residential and Commercial A/C Systems

Sector	Total Cooling Energy Consumption (kWh)	Emissions Factor (g CO_2/kWh)[1]	CO_2 Emissions (MMT)
Commercial	***5.89×10^{11}***	480	**283**
Residential	***4.86×10^{11}***		**233**

Source: World Bank (2014)[209]

B.2 Direct Emissions Estimates

The U.S. EPA estimates direct emissions from global refrigerant usage in the 2012 Global Anthropogenic Non-CO2 Greenhouse Gas Emissions report. Appendix F of the report disaggregates global HFC emissions (MMTCO$_2$e) from the refrigeration and A/C sector by region and sub-sector. Table B-3 summarizes the direct emissions estimate for residential and commercial A/C and chillers. HFC emissions from chillers were added to commercial A/C emissions for this analysis.

Table B-3: 2010 HFC Emissions Estimates (MMTCO$_2$e)

Sector	OECD	Non-OECD Asia	Non-OEDC Europe + Eurasia	Central & South America	Africa	Middle East	Total
Commercial A/C	12.05	3.01	1.44	1.08	0.88	0.51	**18.97**
Residential A/C	12.57	2.72	1.52	1.14	0.93	0.54	**19.42**
Chillers	5.24	1.14	0.64	0.48	0.39	0.23	**8.12**

Source: EPA (2012)[210]

[209] Foster, Vivien, and Daron Bedrosyan. 2014. "Understanding CO2 Emissions from the Global Energy Sector." World Bank. http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2014/02/24/000456286_20140224131751/Rendered/PDF/851260BRI0Live00Box382147B00PUBLIC0.pdf.
[210] EPA. 2012. "Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990 - 2030." United States Environmental Protection Agency. https://www3.epa.gov/climatechange/Downloads/EPAactivities/Appendices_Global_NonCO2_Projections_Dec2012.pdf.

While HCFCs are undergoing an accelerated phase out per the Montreal Protocol, HCFC-22 is still in widespread use for A/C applications, especially in Article 5 nations. HCFC-22 is a powerful greenhouse gas, and is currently controlled under the Montreal Protocol in consideration of both its ozone depletion and high global warming potentials. However, it is not included in IPCC or EPA fluorinated gas emissions totals because it is not included in the Kyoto Protocol, the international treaty that specifically addresses greenhouse gases. In the absence of disaggregated data by sector, we developed estimates of A/C-related HCFC-22 emissions using a "top-down" approach based on atmospheric concentrations, as opposed to the "bottom-up" approach used for HFCs, which relies on estimates of charge size and leakage rates for each equipment type. Xiang, et al. (2014) provides an estimate of global HCFC-22 emissions in 2010, in gigagrams (Gg, not CO_2-eq). We then attribute a portion of this total to A/C systems by applying a percentage of total HCFC-22 *consumption* attributable to A/C systems, reported by the World Bank. This approach implicitly assumes that proportional *emissions* attributions are equivalent to proportional *consumption* attributions. We believe this is a reasonable assumption due to the fact that end-of-life refrigerant recovery is less likely in countries still using R-22 equipment. Table B-4 details the derivation of total global HCFC-22 emissions attributable to A/C systems using the following equation:

$$\boldsymbol{E}_{\boldsymbol{HCFC-22,CO_2eq}}\,(MMT) = \boldsymbol{E}_{\boldsymbol{HCFC-22}}\,(gG)\;x\;\boldsymbol{P}_{\boldsymbol{AC}}\,(\%)x\;\boldsymbol{GWP}_{\boldsymbol{HCFC-22}}\;x\;\frac{\boldsymbol{10^{-3}\,MMT}}{\boldsymbol{1\,Gg}}$$

$\boldsymbol{E}_{\boldsymbol{HCFC-22,CO_2eq}}$ = Global CO_2-equivalent emissions of HCFC-22 from A/C systems

$\boldsymbol{E}_{\boldsymbol{HCFC-22}}$ = Total global HCFC-22 emissions

$\boldsymbol{P}_{\boldsymbol{AC}}$= Percentage of total emissions attributable to A/C systems

$\boldsymbol{GWP}_{\boldsymbol{HCFC-22}}$ = Global warming potential of HCFC-22

Table B-4: 2010 HCFC-22 Emissions Estimate

Total Emissions (Gg/yr.)	Percent Attributable to Air Conditioning	GWP	Total A/C HCFC-22 Emissions ($MMTCO_2e$)
350	21%	1,760	**129**

Sources: Xiang et al. (2014)[211] World Bank/ICF (2007)[212], IPCC (2013)[213]

[211] Xiang., et al. 2014. "Global Emissions of Refrigerants HCFC-22 and HFC-134a: Unforeseen Seasonal Contributions." Proceedings of the National Academy of Sciences of the United States of America 111 (49): 17379–84 http://www.pnas.org/content/111/49/17379.full

[212] ICF. 2007. "Assessment of HCFC-Based Air Conditioning Equipment and Emerging Alternative Technologies." Prepared for The World Bank Montreal Protocol Operations Environment Department. http://siteresources.worldbank.org/INTMP/1114786-1212782394642/21795331/HCFCACAssessmentFinalReport.pdf.

[213] IPCC. 2013. "Climate Change 2013 The Physical Science Basis" Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Available at: http://www.ipcc.ch/pdf/assessment-report/ar5/wg1/WG1AR5_Frontmatter_FINAL.pdf

Total A/C-related HCFC-22 emissions are disaggregated into residential and commercial sectors by assuming the proportion of HCFC-22 emissions attributable to each of these systems is equal to the proportional attribution of HFC emissions. Table B-5 reports this breakdown.

Table B-5: Disaggregation of 2010 HCFC-22 A/C Emissions

Sector	Total A/C HCFC-22 Emissions ($MMTCO_2e$)	HFC Attribution (from Table B-3)	HCFC-22 Emissions by Sector
Commercial	**129**	27.54 *(58%)*	**75**
Residential		19.42 *(42%)*	**54**
Total		46.51	-

Appendix C: Low-GWP A/C Equipment Status

The table below provides full sources for Table 4-7 and Table ES-1.

Status of A/C Equipment Categories with Low-GWP Refrigerant Options Showing Comparable or Improved Performance and Efficiency

	Equipment	Status	U.S. SNAP Application Submitted [a]	Examples	
				Best GWP	Detail
Residential	Room and portable	●	✓	<10	R-32;[b] R-290[c]
Residential	Ducted split & single-package	◔	✓	<700	Multiple candidates[d]
Residential	Ductless split system	●	✓	<10	R-32;[e] R-290[f]
Commercial	Packaged terminal	◕	✓	<700	R-32[g]
Commercial	Packaged rooftop unit	◔	✓	<700	Multiple candidates[h]
Commercial	Ductless (VRF/VRV)	◕		<700	R-32[i]
Commercial	Scroll / recip. chiller	◔	✓	<700	DR-55 (R-452B)[j]
Commercial	Screw chiller	●	✓	<10	R-513A; R-1234ze(E)[k]
Commercial	Centrifugal chiller	●	✓	<10	R-1233zd(E), R-1234ze(E)[l]

● Commercially available in some global markets; ◕ Product under development; ◔ Tested in Lab

Table references:

a. For all residential categories, as well as "Packaged terminal" and "Packaged rooftop unit" commercial categories: Daikin, 2011. Significant New Alternatives Policy Program Submission to the United States Environmental Protection Agency for HFC–32 in residential and light commercial air conditioning. [Signed: 6/13/2011]. For Chillers: EPA-HQ-OAR-2003-0118-1234 – submission for XP30 (R-514A) for "chillers" and EPA-HQ-OAR-2003-0118-1290 – submission from DuPont Fluoroproducts [now Chemours] for HFO-1336mzz(Z) for chillers, industrial process AC, heat transfer fluid [signed: 2/19/2015].

b. "LG Supplies R32 Air Conditioners in US." 2016. Accessed June 7. http://www.coolingpost.com/world-news/lg-supply-r32-air-conditioners-in-the-us/.

c. EPA. 2013. "Energy Star Room Air Conditioners Framework Document." May 2016. Available at: https://www.energystar.gov/sites/default/files/specs//ENERGY%20STAR%20Room%20Air%20Conditioner%20Framework%20Document.pdf.

d. Amrane, Karim, and Xudong Wang. 2015. "Update on Phase II of the AHRI Low- GWP Alternative Refrigerants Evaluation Program." In Technical Forum on Research Projects for Alternative Refrigerants in High Ambient Countries. Dubai, United Arab Emirates. Accessed May 2016. Available at: http://www.unep.org/ozonaction/Portals/105/documents/events/MOP27/02e%20HA%20Presentation%20AREP%20II-HAT%20Summary%20-%20Final.pdf.

e. Daikin. 2013. "World's First Adoption of R32, a Refrigerant With Low Global Warming Potential." Available: http://www.daikin.com/csr/report/2013/p15_18_feature1.pdf.

f. JARN. 2011. "World's First Production Line of Split AC with R290 Put into Operation." Accessed May 2016. Available at: https://www.ejarn.com/news.aspx?ID=15844.
g. ACHR News. 2015. "HVAC Industry Invests in Low-GWP Refrigerants." Accessed May 2016. Available at: http://www.achrnews.com/articles/130890-hvac-industry-invests-in-low-gwp-refrigerants.
h. Schultz, Ken, Marcos Perez-Blanco, and Steve Kujak. 2015. "System Soft-Optimization Tests of Refrigerant R-32, DR-5A, and DR-55 in a R-410A 4-Ton Unitary Rooftop Heat Pump-Cooling Mode Performance." Available at: http://www.ahrinet.org/App_Content/ahri/files/RESEARCH/AREP_Final_Reports/AHRI_Low_GWP_AREP_Rpt_056.pdf.
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k. Gaved, Andrew. 2016. "Carrier Opts for HFO 1234ze Refrigerants for Global Chiller Range." February 26, 2016. Available at: http://www.racplus.com/news/carrier-opts-for-hfo-1234ze-refrigerants-for-global-chiller-range/10003440.fullarticle
l. ACHR News. 2015. "MHI Introduces Next-Generation Centrifugal Chillers." http://www.achrnews.com/articles/129994-mhi-introduces-next-generation-centrifugal-chillers.

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