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BUILDING TECHNOLOGIES OFFICE

The Future of Air Conditioning for Buildings – Executive Summary

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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 various 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	●	$3.4	Packaged terminal	◕	$0.2
Ducted split & single-package	◔	$3.3	Packaged rooftop unit	◔	$4.6
Ductless split system	●	$48.5	Ductless (VRF/VRV)	◕	$10.7
			Scroll / recip. chiller	◕	
			Screw chiller	●	$8.3 (All chillers)
			Centrifugal chiller	●	

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 the 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

[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.

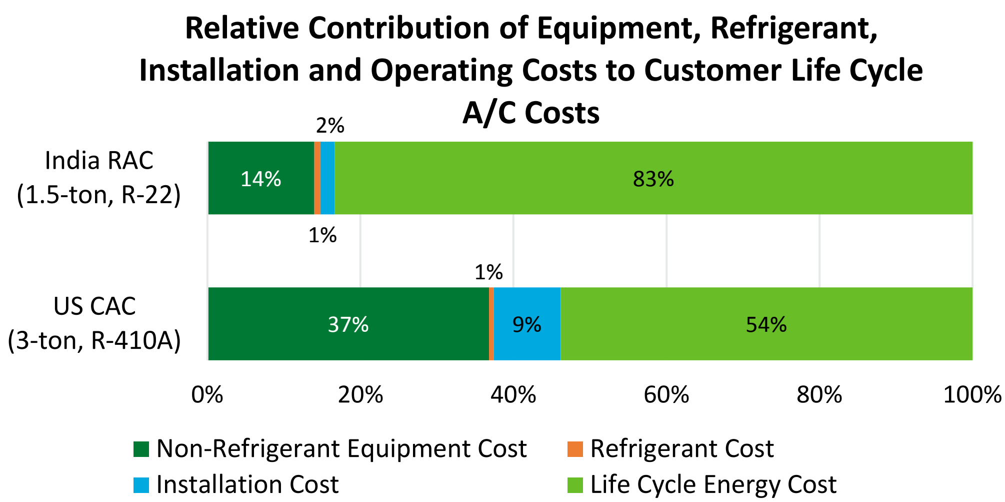

Figure ES-1: Residential life cycle A/C cost breakdown examples[16]

[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 technologies 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.

[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.

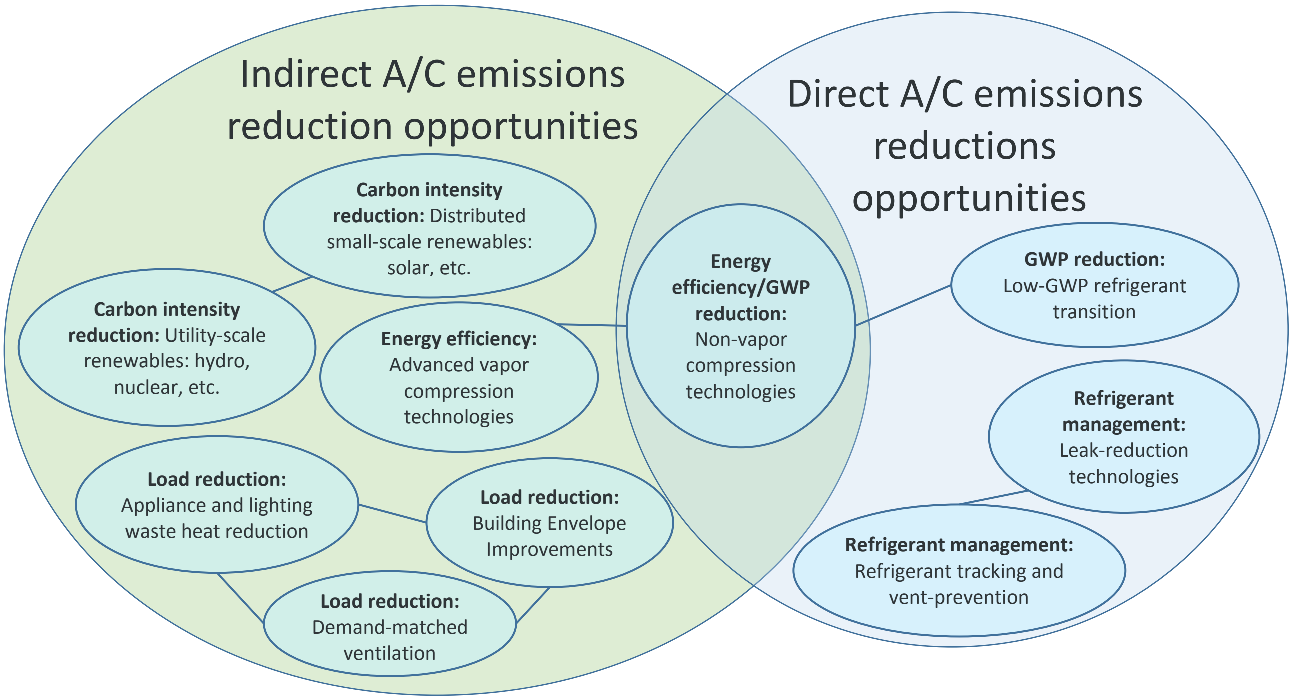

Figure ES-2: Elements of sustainable, low-emissions A/C systems

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.

For more information, please see the full report available at: eere.energy.gov/buildings

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