Alternatives to Vapor-Compression HVAC Technology

BY WILLIAM GOETZLER, MEMBER ASHRAE; ROBERT ZOGG, MEMBER ASHRAE; JIM YOUNG, ASSOCIATE MEMBER ASHRAE; AND CAITLIN JOHNSON, ASSOCIATE MEMBER ASHRAE

Vapor compression using electrically driven compressors has become the dominant HVAC technology due to its scalability, reliability, nontoxic and nonflammable refrigerants, use of electricity, and relatively compact size. While absorption chillers are still popular in Japan and other markets where regulations encourage the use of nonelectric air-conditioning systems, vapor-compression systems provide the majority of space cooling, and a substantial amount of space heating, in the United States.

In 2013, HVAC equipment accounted for 38% of U.S. residential and commercial building primary energy consumption,* with vapor-compression equipment accounting for 11% of space-heating energy consumption and 99% of space-cooling energy consumption, as shown in *Figure 1*.† Depending on the climate and equipment configuration, some type of vapor-compression system can almost always supply space cooling and/or space heating to maintain a comfortable environment within buildings, with relatively high efficiency and moderate cost.

Problems with Current Refrigerants

Vapor-compression systems transport heat through a closed-loop cycle by compressing, condensing, expanding, and evaporating a working fluid (refrigerant). While vapor-compression equipment can use many working fluids, most systems use one of several conventional fluorocarbon refrigerants designed specifically for HVAC applications. Unfortunately, these conventional refrigerants used in vapor-compression systems have detrimental environmental impacts when released into the atmosphere through leaks and other losses during installation, repair, and removal.

While HFC refrigerants facilitated the successful phaseout of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs), HFCs can contribute to global climate change when released to the atmosphere. For example, HFC–134a and HFC–410A have global warming potentials (GWPs) of 1,370 and 2,100‡ times that of carbon dioxide (CO_2), respectively.[2] To curb human-influenced climate change, the United States, Canada,

William Goetzler is a managing director, Robert Zogg is an associate director, and Jim Young is a managing consultant in the Energy Practice of Navigant Consulting. Caitlin Johnson is a graduate student at Boston University, and formerly a senior consultant with Navigant Consulting.

and Mexico announced a proposal in April 2013 to reduce HFC consumption by 85% between 2016 and 2033.[3] In addition, several institutions within the European Union endorsed an agreement to reduce HFC consumption by roughly 80% by 2030.[4] The U.S. Environmental Protection Agency (EPA) announced in February 2014 the development of two rulemakings: one to expand the list of low-GWP refrigerants, and a second to de-list several high-GWP refrigerants for use in air-conditioning and refrigeration applications.[5] As *Figure 2* illustrates, meeting these agreements will require significant action within the HVAC industry to balance the phase-down of high-GWP refrigerants with the rising consumer demand for HVAC and other refrigeration systems.

Researchers have identified several low-GWP alternatives; however, many of these refrigerants suffer from other undesirable characteristics such as flammability, which poses a significant concern under current safety standards. Moreover, alternatives for HFC–134a and HFC–410A may have lower volumetric capacities, while options such as carbon dioxide require complete system redesign due to their transcritical cycle properties.

Additionally, design changes required to address the characteristics of low-GWP refrigerants may significantly raise the costs of vapor-compression systems and could affect overall system efficiency. Because the energy consumed during system operation accounts for the majority of an HVAC system's carbon emissions, maintaining or improving the efficiency of HVAC equipment relative to current technology is an important consideration when developing equipment with low-GWP refrigerants.

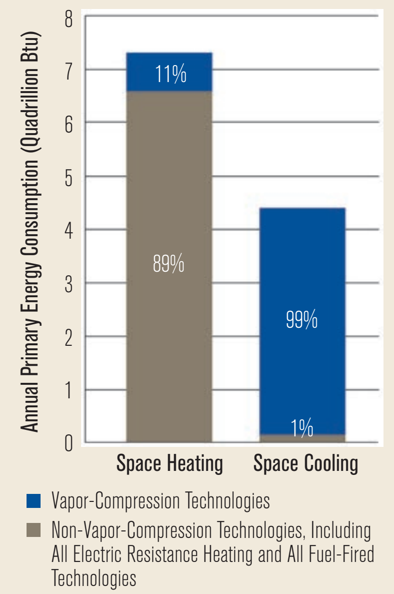
Alternatives to Vapor Compression

Although work is underway to develop alternative refrigerants and improve refrigerant management strategies, the phase-down of HFCs will impose constraints on vapor-compression equipment that will require trade-offs among cost, efficiency, and safety. These constraints could present market opportunities for alternative space-conditioning technologies.

A recent U.S. Department of Energy (DOE) study[7] characterizes alternative technologies based on their development status (some technologies are in very early stages of development), potential for energy savings, and other factors that may affect their ability to compete with vapor-compression systems. *Figure 3* groups 22 non-vapor-compression technologies analyzed in the DOE study, classified by energy source and primary working fluid or material. Although vapor-compression systems are also used in refrigeration, transportation, and process cooling applications, the DOE study focuses solely on building HVAC applications.

Some alternative technologies are impractical for space-conditioning applications due to low efficiencies and capacities (e.g., pulse-tube and vortex-tube cycles), and some are too early in their development cycle to be fully evaluated (e.g., Bernoulli heat pump, critical-flow cycle, and electrocaloric heat pump). The DOE study focuses on the remaining 17 technologies that could serve as viable alternatives in vapor-compression space-heating and space-cooling systems, with some additional development.

FIGURE 1 U.S. building sector HVAC primary annual energy consumption, by technology.[1]



In general, the studied vapor-compression alternative technologies fall into three categories: solid-state, electro-mechanical, and thermally driven technologies.

Solid-State Technologies

Solid-state technologies produce useful temperature differences based on the intrinsic material

*Primary energy accounts for the losses in generation, transmission, and distribution. These losses are only accounted for electricity, as the transmission and distribution losses for natural gas and other fossil fuels tend to be small. Primary energy does not account for the losses associated with extraction.

†The authors developed these estimates using the Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2010[1] to forecast baseline energy consumption in the buildings sector, segregated by geographic location, end use, and fuel type.

‡These GWP values are expected to change upon the publication of the UNEP 5th Assessment Report.

FIGURE 2 Projected GWP-weighted HFC consumption in baseline scenario with no HFC alternatives.[6]

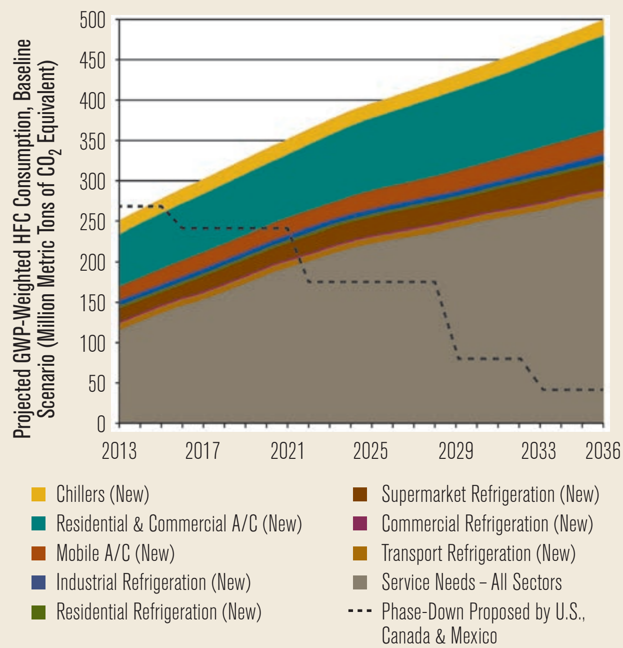
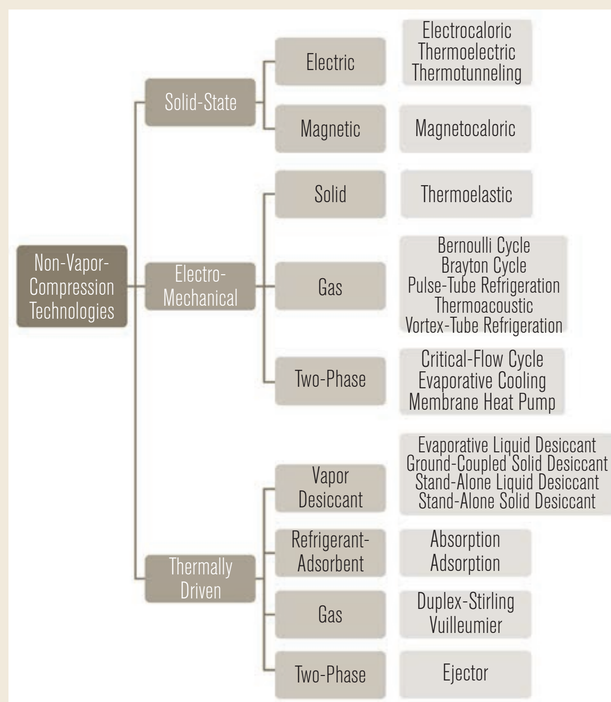


FIGURE 3 Taxonomy of non-vapor-compression technologies.[7]



properties of their core solid-state substance when activated through electrical input.

Magnetocaloric. Some paramagnetic materials exhibit reversible temperature change under a changing magnetic field. Technology based on this magnetocaloric effect is in the prototype development stage for HVAC applications, although some manufacturers are attempting to commercialize magnetocaloric refrigeration within the next few years. The volatile nature of the global supply for rare-earth magnets, however, is a potentially significant barrier to market adoption.

Thermoelectric. These materials generate a temperature difference that can provide space conditioning under an applied voltage. Although thermoelectrics are commercially available in low-capacity and low-lift applications, high-efficiency thermoelectric technology suitable for HVAC applications is still under development.

Thermotunneling. Thermotunneling is a thermoelectric technology that transmits electrons across a nanometer-scale vacuum via quantum tunneling to produce cooling or heating. This technology is in the early stages of research and development (R&D), and the authors were unable to identify any prototypes or demonstrations beyond basic materials research.

Electro-Mechanical Technologies

Electro-mechanical technologies are electrically driven technologies that alter the phase or other properties of a working fluid to pump heat.

Brayton-Cycle Heat Pump. These heat pumps generate usable heating and cooling by compressing and then expanding a gas, typically air, using turbo-machinery. Although common for space cooling in aircraft and trains due to their high reliability and low maintenance requirements, Brayton-cycle heat pumps have limited potential for building space conditioning due to their low coefficients of performance (COPs).

Evaporative Cooling. Evaporative coolers use liquid water to absorb sensible heat from airstreams, evaporating the water and thus cooling the air. These systems have been commercially available for decades for use in hot-dry climates. However, they have achieved very low market penetration because of their inability to meet moisture removal requirements at all times (even in hot-dry climates), as well as high water consumption, the installation complexities of supplying water to equipment, and maintenance concerns.

Membrane Heat Pump. An advanced-membrane heat pump provides cooling and dehumidification by transferring moisture across a number of membranes using a

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vacuum pump. This technology is in the second-generation prototype stage, and uses a membrane already commercialized for energy recovery ventilators.

Thermoacoustic. A thermoacoustic heat pump oscillates a helium-based working fluid using high-amplitude sound waves to generate a temperature gradient as the sound waves compress and expand the gas. Researchers have developed several prototypes for refrigeration applications, but the authors were unable to identify any thermoacoustic prototypes for HVAC applications.

Thermoelastic. This system uses the unique properties of a shape memory alloy (SMA) or special polymers to absorb heat from, or reject heat to, their surroundings as it stresses and releases a SMA core. This technology is in the early stages of R&D, with proof-of-concept prototype development underway for HVAC applications.

Thermally Driven Technologies

Thermally driven technologies use thermal energy as the primary input to drive a heat pump.

Absorption Heat Pump. An absorption system uses a refrigerant-absorbent working-fluid pair and thermal energy source to drive a heating and/or cooling cycle, where the refrigerant is cyclically absorbed and desorbed from the absorbent. Their size, cost, and complexity have presented major barriers to adoption in residential and light commercial applications, despite their commercialization in larger chilled-water systems.

Adsorption Heat Pumps. An adsorption heat pump uses a specialized porous material to adsorb, or capture, a refrigerant, and release the refrigerant at high temperature and pressure when exposed to a heat source. Although commercialized for combined heat and power and solar thermal applications, low system COP and large size are barriers to broader market adoption.

Duplex-Stirling Heat Pump. This heat pump uses the mechanical energy generated by a gas-fired Stirling engine to compress and expand a gaseous refrigerant, transferring it between two chambers, to produce space conditioning. Although Stirling heat pumps have been commercialized in certain refrigeration applications, they have seen minimal development for space-conditioning applications.

Ejector Heat Pump. An ejector heat pump accelerates a refrigerant through a nozzle using a high-pressure non-refrigerant fluid. Ejector-based systems are attractive due to their simplicity, but low COPs limit their use in space-conditioning applications.

Evaporative Liquid Desiccant Air Conditioner (AC). An evaporative liquid desiccant air conditioner consists of a primary channel that dries and cools incoming air using a liquid-desiccant stream, and a secondary channel that evaporatively cools a water layer using a portion of the dried air, further cooling the supply air. Developers have laboratory-tested benchtop units, but have not yet tested full system prototypes. Developers claim that this technology is effective in all climate zones (unlike evaporative coolers that operate effectively in only hot-dry climates).

Ground-Coupled Solid Desiccant AC. This technology combines two technologies: ground-coupled fluid systems and solid desiccants. The primary stage first dries the supply air using a solid desiccant wheel, and the secondary stage sensibly cools the air using a ground-coupled fluid loop. Several non-vapor-compression technologies could provide sensible cooling in the secondary stage, but current prototypes use a ground-coupled fluid system to generate relatively cool water. By first drying the air with desiccants, the ground-coupled system can lower the temperature of supply air, despite its modest temperature lift.

Stand-Alone Liquid Desiccant AC. Liquid desiccant air conditioners use materials with a high affinity for water to absorb moisture from air. Because they dehumidify only, liquid desiccant air conditioners require a supplementary system to remove sensible heat. The aforementioned DOE study evaluated this technology without considering this supplementary system.

Stand-Alone Solid Desiccant AC. This air conditioner absorbs moisture from air using a material with a high affinity for water. HVAC systems incorporating solid desiccants have been commercialized for more than two decades. Because they dehumidify only, they require a supplementary system to remove sensible heat. The DOE study also evaluated this technology without considering this supplementary system.

Vuilleumier Heat Pump. A Vuilleumier heat pump uses a gas-fired heat engine to cyclically compress and expand a gaseous working fluid, typically high-pressure helium, to produce a hot and cold side. Although similar to the Stirling cycle, the Vuilleumier heat pump circulates the working fluid among three volumes of different temperatures, *Advertisement formerly in this space.*

rather than separated working volumes. Researchers are currently developing prototype systems for residential space-conditioning and water-heating applications.

Potential Impacts

For each of the previous 17 alternative technologies, the DOE study compares reported energy savings in cooling and/or heating modes to a baseline vapor-compression technology that meets current energy-conservation standards (or typical current practice, if no standard exists). *Figure 4* shows the energy savings, development status, and geographic applicability of each alternative technology.

Some of the 17 alternative technologies also offer non-energy benefits. For example, thermally activated technologies, many of which can use low-grade heating sources, can still reduce peak electric demand, even if they are less efficient than vapor compression. Additionally, some technology options independently control temperature and humidity, which could provide improved comfort and indoor air quality.

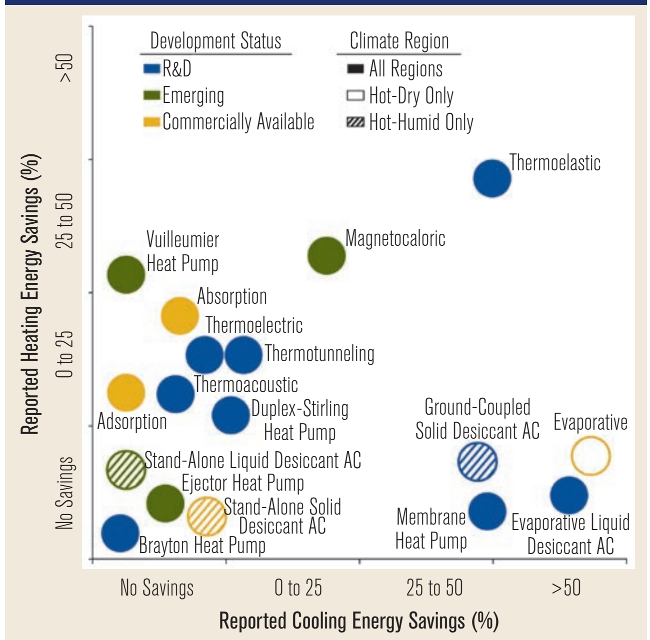
Some alternatives to vapor compression have drawbacks, such as increased noise or safety risks, that might negatively impact market acceptance. Moreover, because some alternatives are less efficient than current vapor-compression equipment, they may have higher life-cycle climate performance (LCCP), a metric that combines direct refrigerant emissions with the indirect emissions associated with electricity generation, transmission, and distribution.

Most Promising Technologies

Table 1 lists the alternatives to vapor compression offering potential for at least 15% energy savings (per installation, based on primary energy) in the heating and/or cooling modes based on available information. While there are, of course, many uncertainties about the ultimate potentials of these alternatives, *Table 1* likely includes the non-vapor-compression technologies that currently offer the most promise in space-heating and space-cooling applications.

As highlighted in the DOE study, thermoelastic and membrane heat pumps are among the technology alternatives that show the most promise, due to their substantial unit energy savings potential, significant non-energy benefits, and relatively simple and inexpensive designs. Both technologies are in the R&D stages, but initial performance of small-scale prototypes suggests good long-term potential for each.

FIGURE 4 Energy savings, development status and geographic applicability of 17 alternatives to vapor compression.



Thermoelastic

A thermoelastic cooling system alternately stresses and releases an SMA regenerator that absorbs heat from the supply air and expels heat to exhaust air. This space-cooling process can be accomplished either cyclically, by timing the oscillation of the regenerator between the two heat sinks, or continuously, by circulating the regenerator in belt form. By altering the timing sequence or circulation, the thermoelastic system could supply space heating as well.

Researchers have demonstrated thermoelastic systems with temperature differentials of ±30°F (17°C) and COPs around 3.[8] Moreover, researchers anticipate that they will improve efficiency further by capturing the mechanical energy created by unloading the SMA core, potentially leading to COPs of 6 or greater.[9]

Through the DOE's Advanced Research Projects Agency–Energy (ARPA-e) program, the University of Maryland and its research partners are currently designing and testing a small-scale breadboard with plans for assembling a full-scale, one ton (12,000 Btu/h [3.5 kW]) window air-conditioner prototype by 2015.

Because the core of these systems will undergo millions of mechanical loading cycles over its life, thermoelastic cooling systems will require highly resilient or

easily replaceable materials to operate successfully. Researchers are currently evaluating various SMAs and other materials that can meet the stringent fatigue properties required by thermoelastic systems.

Membrane Heat Pump

Selectively permeable membranes can very efficiently transport water molecules and thermal energy across their surface, while inhibiting the migration of air and other substances. Manufacturers have already commercialized

TABLE 1 Alternative technologies offering at least 15% energy savings[a] compared to vapor compression.

NON-VAPOR-COMPRESSION TECHNOLOGY	HEATING OPERATION	COOLING OPERATION	DEVELOPMENT STATUS	EXPECTED COST/COMPLEXITY[b]	NON-ENERGY BENEFITS	MARKET BARRIERS
Thermoelastic[c]	✓	✓	R&D	Comparable		Reliability Risks
Membrane Heat Pump[c]		✓	R&D	Comparable	Air Quality, Demand Reduction	Water Use
Absorption Heat Pump	✓	✓	Commercially Available	Moderately Higher	Can Use Low-Grade Thermal Energy, Demand Reduction	Toxicity and/Or Reliability of Working Fluids
Evaporative Cooling		✓	Commercially Available	Comparable	Demand Reduction	Water Use, Reliability Risks, Only Applicable in Hot-Dry Climate Regions
Evaporative Liquid Desiccant AC		✓	R&D	Significantly Higher	Demand Reduction	Water Use, Reliability Risks
Magnetocaloric	✓	✓	Emerging	Moderately Higher	Noise Reduction	
Ground-Coupled Solid Desiccant AC		✓	R&D	Significantly Higher	Can Use Low-Grade Thermal Energy, Air Quality, Demand Reduction	Only Applicable In Hot-Humid Climate Regions
Vuilleumier Heat Pump	✓	✓	Emerging	Slightly Higher	Improved Reliability, Demand Reduction	

[a] Per installation, based on primary energy and year-round operation (heating and cooling), where applicable.
[b] Compared to vapor compression.
[c] These two technologies were ranked highest in the DOE study.[7]

these membranes for water purification and energy recovery ventilators. By evaporating water as it passes through to a partial vacuum, these membranes can also provide space cooling. Under support of DOE's ARPA-e and the Department of Defense's Environmental Security Technology Certification Program, one manufacturer developed a one ton prototype space-conditioning system that performs a two-step dehumidification and cooling process.

In the first stage, a vacuum pump pulls water vapor across an air-to-air membrane and removes moisture from the supply airstream. In the second stage, a chiller, consisting of a water channel lined with the membrane, cools a water loop by evaporating a portion of the water across the membrane. A vacuum pump creates a partial vacuum across the liquid-to-air membrane that evaporates the water as it traverses the membrane. This evaporation chills the remaining water that then travels to a heat exchanger to sensibly cool the warm, dry air from the first stage.

Although prototype development and performance testing are ongoing, the manufacturer projects an energy efficiency ratio (EER) of 26 Btu/W-h or greater through this two-stage conditioning process.[10] Because the membrane first dehumidifies the air, the chilled-water loop only needs to provide sensible cooling. The system can therefore operate at higher chilled-water temperatures compared to systems that must cool and dehumidify in one step. Alternatively, water spray, groundwater coupling, or other non-vapor-compression cooling technologies may be used to provide sensible cooling.

Outlook for the Future

International concern for the high GWP of HFC refrigerants is spurring development of a new generation of low-GWP refrigerants. Just as it adapted to the phase-down of CFC and HCFC refrigerants, the HVAC industry will adapt to future regulatory changes by developing vapor-compression equipment using low-GWP refrigerants. These new refrigerants may, however, significantly impact the costs and/or performance of vapor-compression systems, thus potentially providing opportunities for alternative technologies.

HVAC products using several of the alternative technologies are available today, while others are currently in development. For example, evaporative cooling systems are currently available that may offer cooling energy savings compared to vapor compression. Similarly, existing absorption heat pumps can attain higher heating efficiencies than conventional heat pumps. However, neither technology has achieved wide market acceptance to date because of higher cost and/or lower reliability. Researchers and manufacturers are working to increase the attractiveness of all alternative technologies through improvements in material science, component and system design, and/or advanced control strategies. Two alternative technologies that are among the most promising are membrane heat pumps and thermoelastic heat pumps.

Some alternative technologies offer non-energy benefits that may improve their economics over conventional vapor-compression systems. Fuel-fired absorption or Vuilleumier heat pumps serving both space-heating and cooling loads may offer lower utility bills, especially for colder climates, where lower cooling efficiency is greatly offset by higher heating efficiency. Further, these technologies can use low-grade thermal energy from solar or combined-heat-and-power systems for improved system efficiency. Alternative technologies may facilitate innovative approaches to heat or cool buildings and, more specifically, their occupants. Vapor-compression technology typically becomes more expensive and less efficient as capacity decreases, limiting the practicality of very small-capacity systems. Several of the alternative technologies are modular and could scale more easily. Developing practical, small-capacity systems could enable more de-centralized designs and new packaging schemes for HVAC systems. For example, manufacturers could integrate HVAC modules into factory-assembled wall and ceiling panels, and product designers could create small microclimate systems that provide individual comfort control for the immediate vicinity of building occupants.

Conclusions

The proposed phasedown of HFC refrigerant consumption presents a window of opportunity for non-vapor-compression HVAC technologies. Many alternative technologies have shown promising results in laboratory settings, or in limited testing with benchtop units, but most have yet to be tested as full-scale prototypes. Further research and development is required to demonstrate the viability of alternative technologies, including demonstrating their ability to compete with conventional vapor-compression products on cost, efficiency, reliability, maintenance requirements, occupant comfort, and safety.

For more information on these non-vapor-compression HVAC technologies, please see the DOE study, available on the DOE website.[7]

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