U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Energy Savings Potential and RD&D Opportunities for Commercial Building HVAC Systems

December 2017

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Preface

The Department of Energy's (DOE) Building Technology Office (BTO), a part of the Office of Energy Efficiency and Renewable Energy (EERE) engaged Navigant Consulting, Inc., (Navigant) to develop this report on heating, ventilation, and air conditioning (HVAC) systems for commercial buildings. This report is an update to a 2011 report of the same name and incorporates new market information, technology trends, and BTO research priorities.

The activities identified in this report are Navigant's recommendations to BTO for pursuing in an effort to achieve DOE's energy efficiency goals. Inclusion in this report does not guarantee funding; activities must be evaluated in the context of all potential activities that BTO could undertake to achieve their goals.

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List of Acronyms

A/C	Air Conditioning
ACEEE	American Council for an Energy-Efficient Economy
AEO	U.S. Energy Information Administration's Annual Energy Outlook
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AHU	Air-Handling Unit
AMO	Advanced Manufacturing Office
ARPA-e	Advanced Research Projects Agency - Energy
BAS	Building Automation System
BIHME	Building-Integrated Heat & Moisture Exchange
BTO	Building Technologies Office
CO_2	Carbon Dioxide
CBECS	U.S. Energy Information Administration's Commercial Buildings Energy Consumption Survey
CCHP	Cold-Climate Heat Pump
CEC	California Energy Commission
CHP	Combined Heat and Power
COP	Coefficient of Performance
CRADA	Cooperative Research and Development Agreement
DCKV	Demand Controlled Kitchen Ventilation
DCV	Demand Controlled Ventilation
DEVAP	Desiccant-Enhanced Evaporative A/C System
DOAS	Dedicated Outdoor Air System
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DR	Demand Response
EERE	DOE's Office of Energy Efficiency and Renewable Energy
EIA	U.S. Energy Information Administration
EMS	Energy Management System
ERV	Energy Recovery Ventilator
ESTCP	Environmental Security Technology Certification Program
FDD	Fault Detection and Diagnostics
GHG	Greenhouse Gas
GPG	U.S. General Services Administration's Green Proving Ground
GSA	U.S. General Services Administration
GTI	Gas Technology Institute
GWP	Global Warming Potential
HFO	Hydrofluoroolefin
HHV	Higher Heating Value
HRV	Heat Recovery Ventilator
HVAC	Heating, Ventilation, and Air Conditioning
HVAC&R	Heating, Ventilation, Air Conditioning, and Refrigeration
IAQ	Indoor Air Quality
JARN	Japan Air Conditioning, Heating, & Refrigeration News
KSU	Kansas State University
LBNL	Lawrence Berkeley National Laboratory
MCFC	Metastable Critical-Flow Cycle
MCM	Magnetocaloric Material
MUA	Make-Up Air
NEEA	Northwest Energy Efficiency Alliance

NEEP	Northeast Energy Efficiency Partnerships
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research and Development Authority
O&M	Operations & Maintenance
ORNL	Oak Ridge National Laboratory
PCM	Phase Change Material
PNNL	Pacific Northwest National Laboratory
PTAC	Packaged Terminal Air Conditioner
PV	Photovoltaic
R&D	Research and Development
RD&D	Research, Development, and Demonstration
RPM	Revolutions Per Minute
RTU	Packaged Rooftop HVAC Unit
SMA	Shape Memory Alloy
TAMU	Texas A&M University
TRL	Technology Readiness Level
U.S.	United States
UC	University of California
UMD	University of Maryland
UTRC	United Technologies Research Center
UV	Ultraviolet
VAV	Variable Air Volume
VFD	Variable Frequency Drive
VHP	Vuilleumier Heat Pump
VOC	Volatile Organic Compounds
VRF	Variable Refrigerant Flow
WCEC	Western Cooling Efficiency Center

Executive Summary

The U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy's (EERE's), Building Technologies Office (BTO) commissioned this characterization and technology assessment of heating, ventilation, and air-conditioning (HVAC) systems for commercial buildings. The main objectives of this study were to:

- Identify a wide range of technology options in varying stages of development that could reduce commercial HVAC energy consumption
- Characterize these technology options based on their technical energy-savings potential, development status, non-energy benefits, and other factors affecting end-user acceptance and the ability to compete with conventional HVAC technologies
- Make specific recommendations to DOE and other stakeholders on potential research, development, and demonstration (RD&D) activities that would support further development of the most promising technology options.

According to the U.S. Energy Information Administration's (EIA) 2017 Annual Energy Outlook (AEO), the U.S. commercial building sector will consume approximately 17.83 quadrillion Btu (Quads) of primary energy in 2017.[1] As shown in Figure 1, HVAC systems will consume 5.35 Quads, which is 30% of the total commercial building energy consumption.

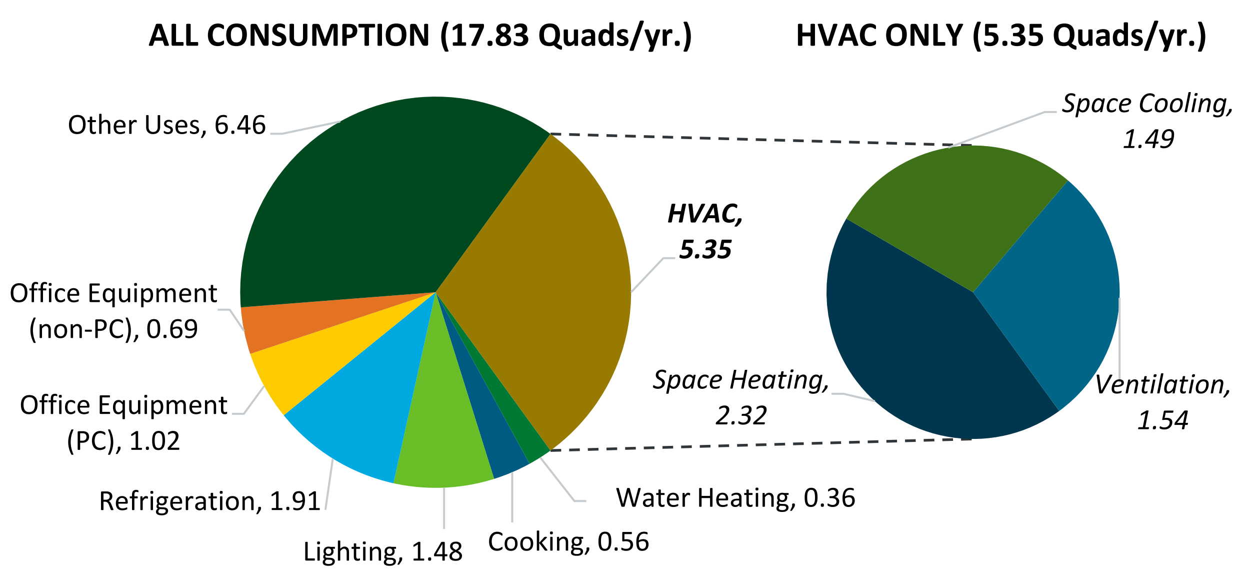

Figure 1: Commercial primary energy consumption by end use, Quads/yr. (2017)

Source: EIA AEO (2017)[2]

[1] Primary energy accounts for the losses in generation, transmission, and distribution. Primary energy does not account for the losses associated with extraction.
[2] EIA. Annual Energy Outlook 2017. Table: Commercial Sector Key Indicators and Consumption. Reference Case. Accessed August 2017. Available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=5-AEO2017&cases=ref2017&sourcekey=0

Most commercial buildings use some form of mechanical HVAC system, with over 90% of commercial floor space using mechanical space heating and space cooling systems.[3] The majority of space heating energy consumption is associated with natural gas, with smaller amounts sourced by electricity, fuel oil, propane, and district heating. Virtually all space cooling systems run on electricity, with a minimal amount associated with thermally activated systems using natural gas or district heating (in the form of steam or hot water). Ventilation systems use electricity-driven fans to circulate outside air throughout a building. The HVAC equipment type and fuel selected for a commercial building varies, depending on the building activity, size, layout, climate, geographic region, existing equipment or distribution system, and other factors.

To develop a priority list of technology options and recommended RD&D activities, we evaluated a broad portfolio of technology options that show promising potential to reduce the energy consumption of commercial HVAC systems. We first conducted a literature search to develop an initial list of over 300 technology options, then screened out those that did not fit the goals of the project (e.g., low unit energy savings, limited applicability to HVAC, etc.). We then selected a subset of 84 technology options for further, more thorough evaluation based on their energy savings potential for commercial HVAC systems. Finally, we conducted a scoring analysis to prioritize the technology options, based on estimates of their technical energy savings potential, upfront cost, operational complexity, non-energy benefits, and peak-demand reduction potential. In addition to the scorecard metrics, we also categorized each technology according to its development status. While this metric is not included as part of the scoring process, we used the technology maturity classifications to select the final list of high priority technology options.

Summary of High Priority Technology Options

Through this process, we selected a final set of 18 high priority technology options for further evaluation that could provide significant HVAC energy savings for U.S. commercial buildings. We grouped similar technologies into the following categories:

- **Technology Enhancements for Current Systems** improve the performance and energy efficiency of the current generation of HVAC equipment and systems.
- **Alternative Electrically Driven Heat Pump Technologies** provide heating or cooling more efficiently, using advanced vapor-compression or non-vapor-compression technologies, and use electricity as the primary energy input.
- **Alternative Gas-Fired Heat Pump Technologies** provide heating or cooling more efficiently, using a thermally activated heat pump cycle, and use natural gas as the primary energy input.
- **Alternative System Architectures** provide localized comfort to building occupants to reduce the operating requirements for traditional HVAC systems.

Table 1 lists the high priority technology options, their estimated technical energy savings potential, and their final ranking. We then developed a detailed profile of each technology that provides an overview of the technology, its current development status and key R&D efforts, projections of performance and energy savings, as well as other attributes that may affect its market uptake.

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[3] EIA. 2016. Commercial Buildings Energy Consumption Survey (2012). Building Characteristics. End-Use Equipment. Tables 39 and 41. Release date May 2016. Available at: https://www.eia.gov/consumption/commercial/data/2012

Table 1: High Priority Technology Options by Category

Technology Category	Technology Option (#)*	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Technology Enhancements for Current Systems	Advanced HVAC Sensors (1)	0.63	3.85
	Building-Integrated Heat and Moisture Exchange Panels (2)	0.53	3.70
	Ventilation Reduction through Advanced Filtration (3)	0.25	3.10
	Surface Coatings for Liquid Friction Reduction (4)	0.12	2.55
Alternative Electrically Driven Heat Pump Technologies	Membrane Cooling System (5)	0.51	3.70
	Metastable Critical-Flow Cycle (6)	0.45	3.65
	Thermoelastic Cooling System (7)	0.41	3.35
	S-RAM Heat Pump (8)	0.25	3.30
	Turbo-Compressor-Condenser-Expander Heat Pump (9)	0.31	2.85
	Electrocaloric Cooling System (10)	0.26	2.85
	Electrochemical Heat Pump (11)	0.21	2.50
	Magnetocaloric Cooling System (12)	0.21	2.50
Alternative Gas-Fired Heat Pump Technologies	Vuilleumier Heat Pump (13)	0.84	3.95
	Ejector Heat Pump (14)	1.01	3.65
	Fuel Cell Combined Cooling, Heating, and Power System (15)	0.37	3.15
Alternative System Architectures	Robotic Personal Comfort Device (16)	0.53	3.80
	Dynamic Clothing Technologies for Personal Comfort (17)	0.53	3.40
	Wearable Devices for Personal Comfort (18)	0.35	2.60

*Numbers refer to order of technology options in this table to serve as reference in Table 2.

Figure 2 highlights the technical energy savings potential of the high priority technology options, by technical maturity. Most technologies could provide approximately 10% energy savings for U.S. space cooling and heating energy consumption for commercial buildings (3.81 Quads/yr. for space cooling and heating, 5.35 Quads/yr. total). Most technologies only provide energy savings for either space cooling or space heating, but some cover all of commercial HVAC energy consumption. HVAC energy savings opportunities for commercial buildings exist across all technical maturity levels, with several technologies in the initial stages of commercialization. Additional research is necessary to demonstrate the performance of the early stage technologies and advance their development towards commercial product readiness and market introduction. At this stage, the energy savings projections for early-stage technologies are likely optimistic, as inefficiencies occur to reach the required capacity for commercial buildings and do not yet include electricity consumption for pumps, fans, and other auxiliary loads.

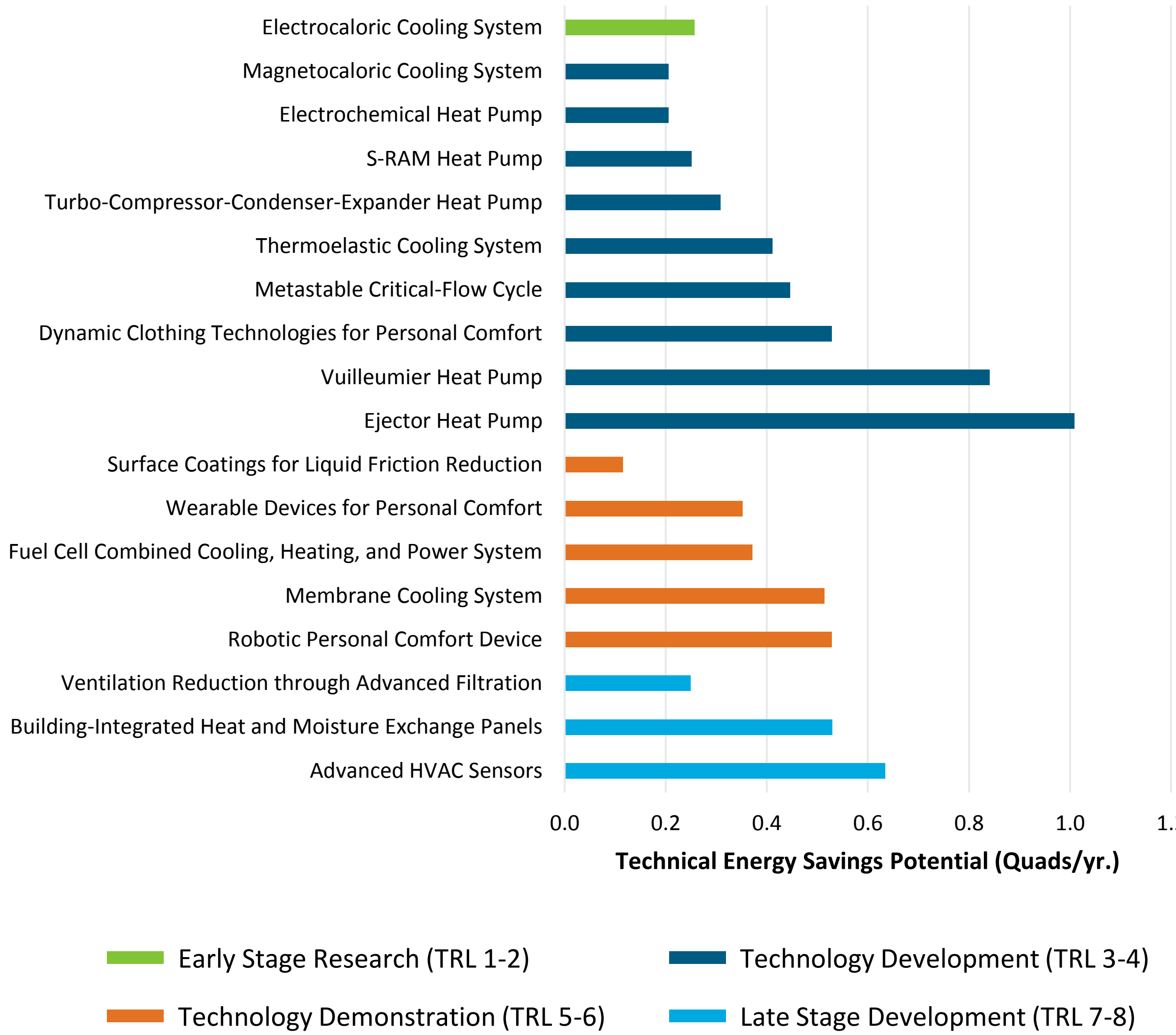

Figure 2: Technical energy savings potential of high priority technology options, by technical maturity

Once fully developed, these technologies are projected to be suitable and attractive for commercial buildings based on their scores in *cost and complexity*, *non-energy benefits*, and *peak-demand reduction potential*. The highlighted terms are discussed below:

- **Cost and Complexity:** Most researchers project reasonable payback periods for these technologies, especially for buildings having high HVAC loads because of their operating hours and/or climate. Regarding complexity, building owners and HVAC system designers value technologies that can easily integrate with existing buildings, do not require substantial changes to building envelopes or distribution systems, have limited size and weight concerns, and do not increase operational or maintenance complexity. Nevertheless, most of the technologies profiled here are in the early-stages of development, and reliable estimates of equipment cost, installation requirements, operating and maintenance costs, etc., are unavailable.

- **Non-Energy Benefits:** Beyond energy savings, each of the high priority technology options provides other benefits that may be attractive to building owners and operators. Benefits such as improved occupant comfort, better indoor air quality (IAQ), lower equipment noise and vibration, and the ability to use zero- or low-global-warming-potential (GWP) working fluids, could support the increased market adoption of these technologies. Many end-users would view comfort and IAQ benefits as having the same level of importance as energy savings.
- **Peak Demand Reduction:** Reducing electrical demand from HVAC systems during peak hours is increasingly important for electric utilities and other stakeholders, as late-afternoon cooling loads often strain the existing capacity of the electrical grid or the availability of power. This can be reflected as higher prices – demand charges or time-of-use prices – for the end-user. Technologies that can reduce electricity capacity requirements by using natural gas (e.g., gas-fired heat pumps) or shifting electricity consumption to off-peak hours (e.g., battery storage for personal comfort devices) would have a significant benefit to both grid operators and, through lower demand charges or peak-hours consumption, building owners. In addition, utilities with high electrical heating adoption on their system experience winter peaking events, and technologies that offer electricity savings during peak winter events are also valuable.

Comparison to Previous 2011 Commercial HVAC Report

BTO commissioned similar studies in 2002[4] and 2011[5] to characterize commercial HVAC energy consumption and identify promising technologies for RD&D support. This study builds on those previous research projects and employs a similar methodology for identification, prioritization, and characterization of commercial HVAC technology options, but with several key changes: First, the market landscape for commercial HVAC systems has changed substantially in recent years, as higher federal appliance efficiency standards, awareness of high-performance building specifications, advancements in communication, software, and control systems, anticipated refrigerant phase-down agreements, and other trends compel the HVAC industry develop new technologies. Second, new market information is available from EIA's 2012 Commercial Building Energy Consumption Survey (CBECS), 2017 AEO, and other resources, to estimate the energy consumption of commercial HVAC equipment. Third, BTO is focusing more of its research towards early-stage technology development, rather than deployment support for commercialized technologies.

We included each of the 2011 technology options on the initial list, but screened several from further consideration because of the increased focus on early-stage technology development. Many of these technologies (e.g., retro-commissioning, ductwork in conditioned space) still offer large energy savings when performed on existing buildings. We did analyze most of the technologies as part of the preliminary research and analysis phase, and we include brief summaries in the appendices. One technology, magnetic cooling cycle, is in the high priority list for both reports, which highlights its continued need for technical improvement and its market attractiveness for building HVAC and other applications.

Recommended RD&D Activities

Based on our review of the high priority technology options for commercial HVAC systems, we recommend that DOE BTO and industry stakeholders pursue the RD&D activities listed in Table 2. Most of the high priority technology options are in the early stages of benchtop testing and prototype development, and therefore require sustained RD&D support to reach market introduction and subsequent wider

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[4] Roth et al. 2002. "Energy Consumption Characteristics of Commercial Building HVAC Systems Volume III: Energy Savings Potential." TIAX LLC. Prepared for DOE Building Technology Program. July 2002. Available at: https://www1.eere.energy.gov/buildings/publications/pdfs/commercial_initiative/hvac_volume3_final_report.pdf
[5] Goetzler et al. 2011. "Energy Savings Potential and Research, Development, & Demonstration Opportunities for Commercial Building Heating, Ventilation, and Air Conditioning Systems." Navigant Consulting Inc. Prepared for BTO. September 2011. Available at: https://energy.gov/sites/prod/files/2014/07/f17/commercial_hvac_research_opportunities.pdf

commercialization. As such, many technologies share a similar development path of component design, laboratory-based testing, prototype development, field testing, and other activities. Table 2 provides a list of applicable technology options that would benefit from each activity. In general, DOE has a primary role in supporting the initial laboratory R&D of early-stage technologies, with industry organizations supporting product demonstration and deployment strategies. Nevertheless, most of the activities outlined in this section will with collaboration from research organizations, manufacturers, utilities, and other industry organizations.

Table 2: Recommended RD&D Activities

Type	Activity	Applicable Technology Options*
Initial Research	Conduct laboratory research on the fundamental physics of the metastable critical-flow cycle	6
	Continue research into advanced caloric materials	7, 10, 12
Component Development	Continue development and testing of advanced membrane-based components	5, 11, 15
	Conduct research to improve binary-fluid and ejector geometry selection for different applications	14
	Continue development of low-cost, wireless HVAC sensor technologies	1
	Develop fabrics incorporating different dynamic clothing technology concepts	17
Laboratory Testing	Conduct laboratory testing with benchtop prototypes to understand the performance and efficiency of the technology and guide future development	4, 5, 6, 7, 8, 10, 12
	Conduct laboratory testing with full-scale prototypes to understand performance and efficiency when including auxiliary loads	9, 13, 14, 15, 16
	Conduct laboratory research on occupant comfort preferences when using alternative system architectures	16, 17, 18
Field Demonstration	Conduct field demonstrations in commercial buildings with pre-production technology prototypes	1, 2, 3, 4, 5, 8, 12, 13, 15
	Conduct field demonstrations of alternative system architectures with different temperature set point schedules	16, 17, 18
System Integration	Collaborate with manufacturers to integrate surface coatings into their production processes	4
	Collaborate with building automation and HVAC controls vendors to integrate technologies into building controls systems	1, 16, 17, 18
Deployment Support	Develop spreadsheet and building modelling tools for HVAC system designers	2, 13, 15
	Collaborate with building code agencies and other stakeholders to increase the feasibility of projects	2, 3, 15

* Numbers refer to technology options list in Table 1

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1 Introduction

The U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy's (EERE's), Building Technologies Office (BTO) commissioned this characterization and technology assessment of heating, ventilation, and air-conditioning (HVAC) systems for commercial buildings. The main objectives of this study were to:

- Identify a wide range of technology options in varying stages of development that could reduce commercial HVAC energy consumption
- Characterize these technology options based on their technical energy savings potential, development status, non-energy benefits, and other factors affecting end-user acceptance and their ability to compete with conventional HVAC technologies
- Make specific recommendations to DOE and other stakeholders on potential research, development, and demonstration (RD&D) activities that would support further development of the most promising technology options.

BTO commissioned similar studies in 2002[6] and 2011[7] to characterize commercial HVAC energy consumption and identify promising technologies for RD&D support. This study builds on those previous research projects and employs a similar methodology for identification, prioritization, and characterization of commercial HVAC technology options, but with several key changes. First, the market landscape for commercial HVAC systems has changed substantially in recent years, as higher federal appliance efficiency standards, awareness of high-performance building specifications, advancements in communication, software, and control systems, anticipated refrigerant phase-down agreements, and other trends compel the HVAC industry develop new technologies. Second, new market information is available from the U.S. Energy Information Agency's (EIA's) 2012 Commercial Building Energy Consumption Survey (CBECS), 2017 Annual Energy Outlook (AEO), and other resources, to estimate the energy consumption of commercial HVAC equipment. Third, BTO is focusing more of its research towards early-stage technology development, rather than deployment support for commercialized technologies. Section 8.6 further describes the changes between this report and the 2011 report.

1.1 Report Organization

Table 3 summarizes the contents of each section of the report. The majority of this report (Section 3 through Section 7) consists of detailed profiles of the high priority technology options identified for commercial HVAC systems.

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[6] Roth et al. 2002. "Energy Consumption Characteristics of Commercial Building HVAC Systems Volume III: Energy Savings Potential." TIAX LLC. Prepared for DOE Building Technology Program. July 2002. Available at: https://www1.eere.energy.gov/buildings/publications/pdfs/commercial_initiative/hvac_volume3_final_report.pdf

[7] Goetzler et al. 2011. "Energy Savings Potential and Research, Development, & Demonstration Opportunities for Commercial Building Heating, Ventilation, and Air Conditioning Systems." Navigant Consulting Inc. Prepared for BTO. September 2011. Available at: https://energy.gov/sites/prod/files/2014/07/f17/commercial_hvac_research_opportunities.pdf

Table 3: Report Organization

Section	Content / Purpose
Executive Summary	Top-level report summary on energy consumption; energy savings opportunities; comparison to 2011 Commercial HVAC Report; and recommended RD&D activities
Introduction	Brief introduction of the scope and objectives of the report, plus background information
Project Approach	Methodology used for technology identification, prioritization, and analysis
Summary of High Priority Technology Options	Brief introduction and summary of the 18 high priority technology options
Detailed Profiles for High Priority Technology Options	Profiles of the 18 high priority technology options, summarizing: technology description; development status; energy savings estimates; technology cost; complexity; peak demand impacts; non-energy benefits; and other attributes
Conclusions	Key observations regarding the high priority technology options and comparison with 2011 Commercial HVAC report
Recommendations	Summary of key RD&D activities recommended to advance the development and market adoption of high priority technology options
Appendix A. Technology Option Scoring	Table summarizing the results of the technology option scoring process
Appendix B: Descriptions of Commercialized High Priority Technology Options	Brief description of each commercialized high priority technology option
Appendix C: Descriptions of Lower Priority Technology Options	Brief description of each secondary technology option

1.2 Background – Commercial HVAC Systems

Nearly all commercial buildings within the U.S. use HVAC systems to provide space conditioning for building occupants. As shown in Figure 3, the latest CBECS survey determined that some type of mechanical space heating and space cooling system is employed in over 90% of commercial floor space.[8] The HVAC equipment type and fuel selected for a commercial building varies, depending on the building activity, size, orientation, climate, geographic region, existing equipment or distribution system, and other factors. In addition, most commercial buildings require a mechanical ventilation system to introduce outside air and maintain indoor air quality (IAQ).

[8] EIA. 2016. Commercial Buildings Energy Consumption Survey (2012). Building Characteristics. End-Use Equipment. Tables 39 and 41. Release date May 2016. Available at: https://www.eia.gov/consumption/commercial/data/2012/

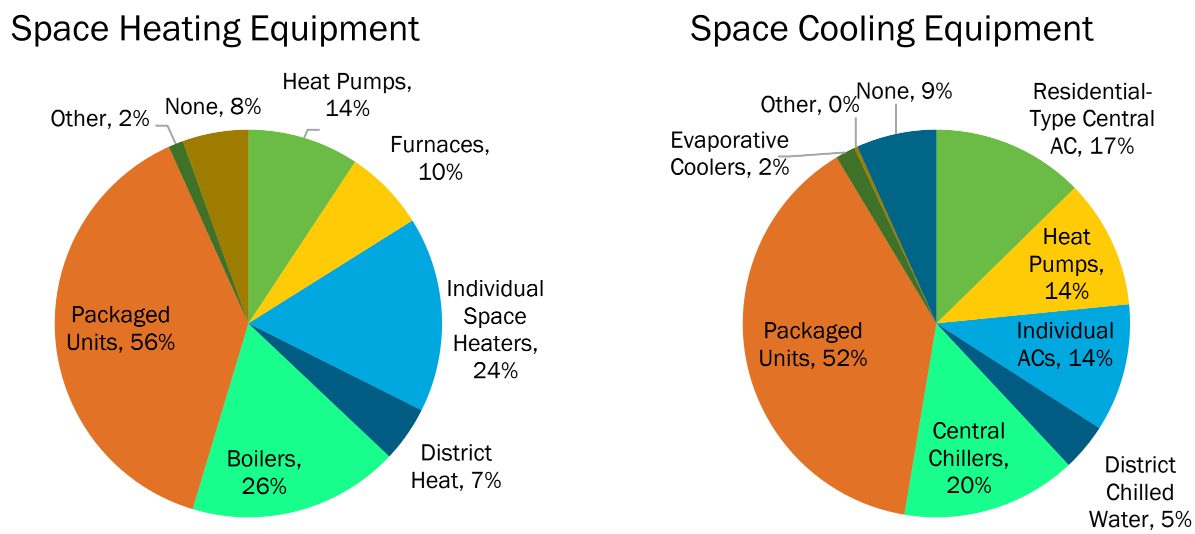

Figure 3: Breakdown of U.S. commercial floor space by HVAC equipment type

Source: CBECS 2012 – Note: more than one system may apply for each building [9]

1.3 Breakdown of Commercial HVAC Energy Consumption

According to the 2017 AEO, the U.S. commercial building sector will consume approximately 17.83 quadrillion Btu (Quads) of primary energy in 2017.[10] As shown in Figure 4, HVAC systems will consume 5.35 Quads, which is 30% of the total commercial building energy consumption. The HVAC energy consumption value consists of 43% for space heating, 28% for space cooling, and 29% for ventilation.

[9] EIA. Annual Energy Outlook 2017. Table: Commercial Sector Key Indicators and Consumption. Reference Case. Accessed August 2017. Available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=5-AEO2017&cases=ref2017&sourcekey=0
[10] Primary energy accounts for the losses in generation, transmission, and distribution. Primary energy does not account for the losses associated with extraction.

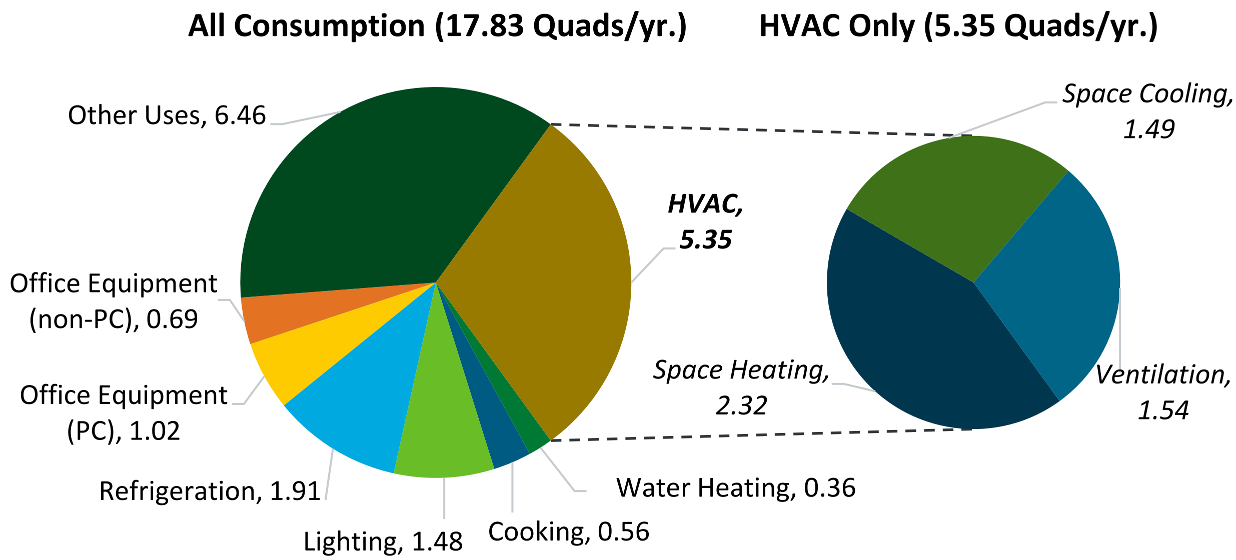

Figure 4: Commercial primary energy consumption by end use, Quads/yr. (2017)

Source: EIA AEO (2017)[11]

Figure 5 provides a breakdown of HVAC energy consumption by end use and fuel type. Most space heating energy consumption is associated with natural gas, with smaller amounts sourced by electricity, fuel oil, propane, and district heating. Virtually all space cooling systems run on electricity, with a minimal amount associated with thermally activated systems using natural gas or district heating (in the form of steam or hot water). Ventilation systems use electricity-driven fans to circulate outside air throughout the building. A portion of space cooling and space heating energy consumption is associated with conditioning outside air to indoor conditions, but AEO does not break out this energy consumption from other space cooling and heating use. Because it accounts for nearly all of overall HVAC energy use, this study focuses on the consumption of electricity and natural gas associated with commercial HVAC systems.

[11] EIA. Annual Energy Outlook 2017. Table: Commercial Sector Key Indicators and Consumption. Reference Case. Accessed August 2017. Available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=5-AEO2017&cases=ref2017&sourcekey=0

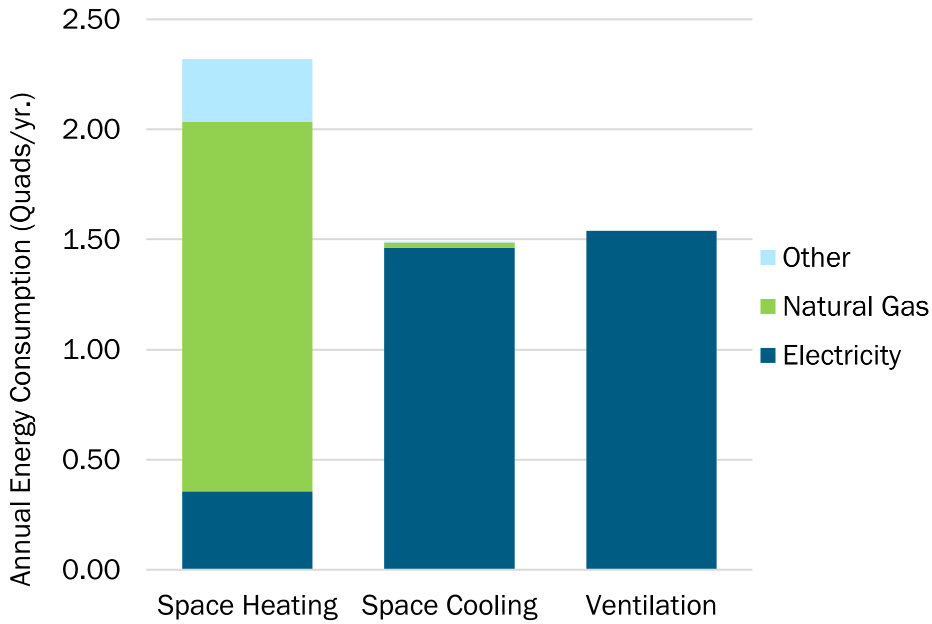

Figure 5: Commercial HVAC primary energy consumption by end use and fuel type (2017)

Source: EIA AEO (2017)[12]

As discussed in Section 1.2, commercial buildings use a variety of HVAC equipment types. Figure 6 and Figure 7 provide a breakdown of space heating and space cooling energy use by equipment and fuel type. These estimates of equipment- and system-level HVAC energy consumption come from the 2017 BTO Scout Tool, which leverages the latest information from 2017 AEO and other resources. Because each technology option is only applicable to certain HVAC equipment types, we use the BTO Scout Tool's estimates to determine the technical energy savings potential for each technology option.

[12] EIA. Annual Energy Outlook 2017. Table: Commercial Sector Key Indicators and Consumption. Reference Case. Accessed August 2017. Available at: https://www.eia.gov/outlooks/aeo/data/browser/#/?id=5-AEO2017&cases=ref2017&sourcekey=0

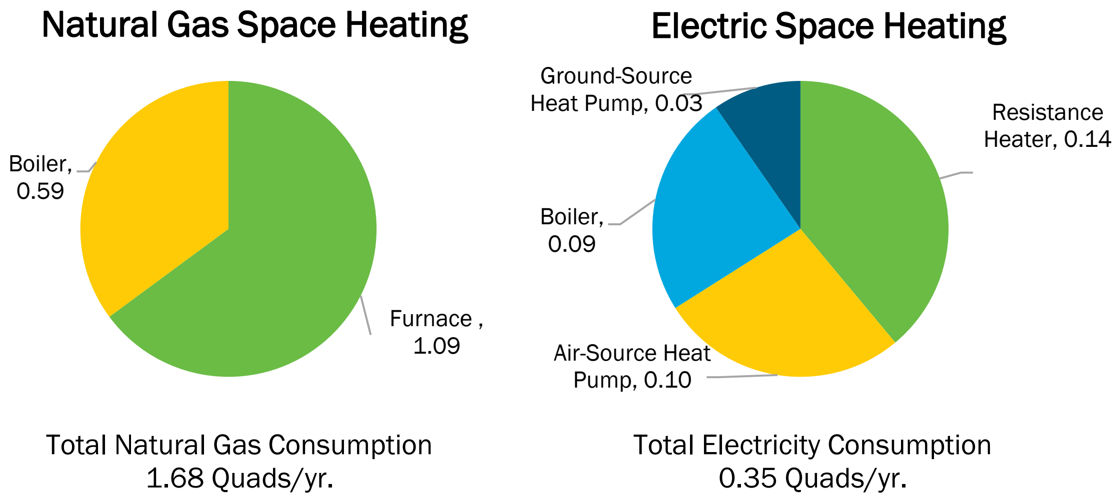

Figure 6: Commercial space heating energy consumption, by equipment type

Source: BTO Scout Tool (2017)[13]

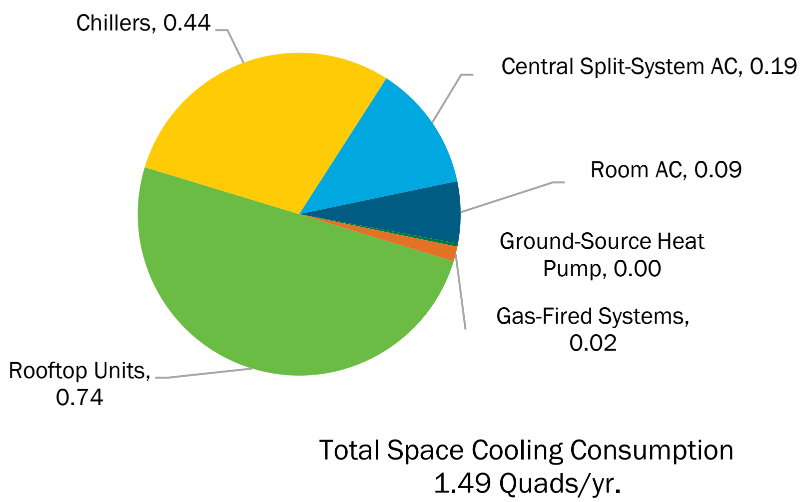

Figure 7: Total commercial space cooling energy consumption, by equipment type

Source: BTO Scout Tool (2017)[14]

[13] BTO. 2017. Scout Baseline Energy Calculator. Accessed August 2017. Available at: https://trynthink.github.io/scout/calculator.html. The Scout tool uses baseline data from EIA Annual Energy Outlook 2017. Additional information is available at: https://energy.gov/eere/buildings/scout

[14] Ibid

2 Project Approach

We examined a broad portfolio of technology options in this project in order to identify a set of technology options that show promise to reduce the energy consumption of commercial HVAC equipment. Figure 8 provides a summary of the technology selection, screening, and assessment processes.

We first conducted a broad literature search to develop an initial list of technology options. From the initial list we then selected a subset of technology options for further, more thorough evaluation, based on their estimated or known energy savings capabilities for commercial HVAC systems. Finally, we conducted a scoring analysis to prioritize and select a final set of 18 high priority technology options for in-depth analysis, including calculation of the technical energy-savings potential and evaluation of the state of technology development.

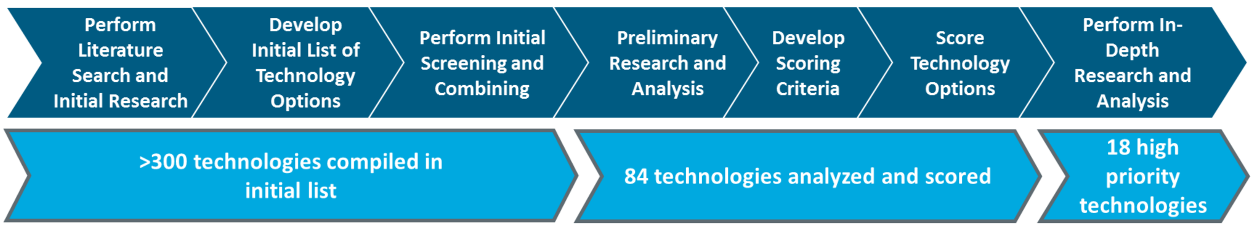

Figure 8: Technology selection, screening, and assessment process

2.1 Initial List of Technology Options

We first generated the initial, comprehensive list of technology options with potential to improve the efficiency of commercial HVAC systems. That list contained over 300 options. During the scanning process we gathered information that included technical descriptions, performance projections, and the applicability of various types of equipment and systems. We compiled the initial list without considering technology maturity, market adoption, energy savings, or cost effectiveness, which would be evaluated in later steps. The following list summarizes the sources we reviewed:

- HVAC industry publications, organizations, and websites. Examples: ASHRAE, Air-Conditioning, Heating, and Refrigeration Institute [AHRI], and Japan Air Conditioning, Heating, & Refrigeration News [JARN]
- U.S. and international government organizations and National Laboratories. Examples: BTO, U.S. General Services Administration's Green Proving Ground [GSA GPG], Advanced Research Projects Agency - Energy [ARPA-e], Oak Ridge National Laboratory [ORNL], Lawrence Berkeley National Laboratory [LBNL], National Renewable Energy Laboratory [NREL], Pacific Northwest National Laboratory [PNNL], California Energy Commission [CEC], and New York State Energy Research and Development Authority [NYSERDA]
- University-based research. Examples: University of Maryland [UMD], Purdue University, University of Illinois, and Texas A&M University [TAMU]
- HVAC manufacturers. Examples: Trane, Daikin, Honeywell, and Johnson Controls
- Gas and electric utility energy efficiency programs. Examples: PG&E, ComEd, and Nicor Gas
- Energy efficiency organizations. Examples: Northwest Energy Efficiency Alliance [NEEA], Northeast Energy Efficiency Partnerships [NEEP], American Council for an Energy-Efficient Economy [ACEEE]
- Internal Navigant sources and HVAC experts.

2.2 Initial Screening and Combining

After completing the initial list of technology options, we developed a set of criteria to screen the options to identify those that warranted further evaluation. We screened out approximately two-thirds of the technology options because they did not meet one or more of the criteria listed below:

1. **Outside of the scope of this study:** These included building design, envelope, lighting, or behavioral strategies that reduce HVAC energy consumption indirectly. For example, improving building insulation reduces HVAC energy waste, but is not itself part of any HVAC equipment or systems.
2. **At the end of their development cycle:** Technologies that are either widely practiced in the HVAC industry or otherwise fully developed into a commercially available product.
3. **Limited or no energy-savings impact:** This included technologies having documented unit energy savings of less than 5% for the overall HVAC system, or less than 15% for a particular component. These technologies may reduce material, lower operating costs, or have other benefits, but do not meet a minimum energy savings threshold.
4. **Limited applicability to commercial HVAC:** These are technologies that do not have direct commercial HVAC applications, but are developed primarily for other purposes such as refrigeration, automotive air conditioning (A/C), or industrial processes. If these technologies were used in commercial building HVAC, the use would only be for niche applications.

After the initial screening, we combined technology options that were variations of the same process (e.g., several technologies were essentially fan improvements) or achieved energy savings by a similar process (e.g., wearable devices for localized comfort).

2.3 Preliminary Research and Analysis

Eighty-four technology options passed the initial screening and combining process. We then conducted a preliminary analysis of those options. The goal of this analysis was to capture key performance details about the technologies and develop a more complete understanding of their potential for energy savings in commercial HVAC systems. Key analysis attributes included: estimated unit energy savings, technology maturity, current R&D and commercialization efforts, demonstrated performance to date, potential non-energy benefits, and projected installed cost. The information gathered at this stage provides the basis for the subsequent scoring analysis and prioritization processes, described in Sections 2.4 and 2.5.

2.4 Development of Scoring Criteria

After the preliminary analysis of the 84 screened technology options, we conducted another round of technology screening using the scoring metrics outlined in Table 4.

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Table 4: Definitions for Technology Scoring Metrics

Metric	Key Question	Definition
Technical Energy Savings Potential	*How much energy could the technology save for U.S. commercial buildings?*	Estimated technical energy savings potential of the technology for target markets, assuming 100% adoption. Estimates were calculated using primary energy consumption estimates from the BTO Scout Tool and unit energy savings percentages from research literature.
Upfront Cost	*Does the technology have higher or lower upfront cost?*	Estimated incremental first cost and installation cost of the technology for target building segment
Operational Complexity	*Does the technology have higher or lower operational complexity?*	Comparison of the technology's operations and maintenance (O&M) requirements, reliability, and other operating characteristics, relative to conventional systems
Non-Energy Benefits	*Does the technology have significant, quantified non-energy benefits?*	Potential of the technology to provide benefits beyond energy savings, including but not limited to: decreased direct global-warming-potential (GWP) impact, improved comfort, improved IAQ, simplified maintenance, and reduced noise/vibration
Peak Demand Reduction Potential	*How much impact will the technology have on electricity demand during peak hours?*	Estimated impact that the technology would have on electrical peak demand (kW), above what their annual energy consumption savings (kWh, Th) would suggest. Note: Impact may be positive or negative.

Table 5 shows the scorecard we developed to assign a numerical score to each technology option. We created a five-point scale for each metric to evaluate the impact of each technology. Each metric was also assigned a weighting to reflect its overall importance to DOE's goal of widespread commercial HVAC energy savings.

Table 5: Technology Prioritization Scorecard

Metric	Weight	1	2	3	4	5
Technical Energy Savings Potential	50%	< 0.10 Quads/yr.	0.10-0.23 Quads/yr.	0.23-0.36 Quads/yr.	0.36-0.50 Quads/yr.	>0.50 Quads/yr.
Upfront Cost	15%	Significantly higher upfront cost	Moderately higher upfront cost	Neutral	Moderately lower upfront cost	Significantly lower upfront cost
Operational Complexity	15%	Significantly higher complexity	Moderately higher complexity	Neutral	Moderately lower complexity	Significantly lower complexity
Non-Energy Benefits	15%	Potential for moderate drawbacks	Provides few or no benefits	Potential for significant benefits, but not well documented	1-2 quantified benefits	Extensive, quantified benefits
Peak Demand Reduction	5%	>10% additional increase	0-10% additional increase	No additional impact	0-10% additional reduction	> 10% additional reduction

In addition to the scorecard metrics, we also categorized each technology according to its development status. Table 6 lists the technology maturity classifications. While this metric is not included as part of the scoring process, we used the technology maturity classifications to select the final list of high priority technology options.

Table 6: Technology Maturity Categorization

Metric	Key Question	Definition and Maturity Classifications
Technology Maturity	*Is DOE support critical for the technology's development?*	Suitability of activity to BTO's mission, goals, and capabilities. (E.g., early-stage, disruptive R&D is core to DOE's mission, while incremental or deployment support R&D is not.) - Early Stage Research (TRL 1-2) - Technology Development (TRL 3-4) - Technology Demonstration (TRL 5-6) - Late Stage Development (TRL 7-8) - Full Commercialization

2.5 Scoring Technology Options

Using this scorecard, plus our research and the input of HVAC experts within Navigant, we scored each of the 84 technology options. Figure 9 presents the scores of the top-rated technology options. With a goal of highlighting the technologies most aligned with DOE's R&D mission, we further screened out technologies that have already achieved full commercialization, as highlighted in Figure 9. Through this process, we identified the 18 technologies that clearly scored above the rest and best fit the goals of this report.

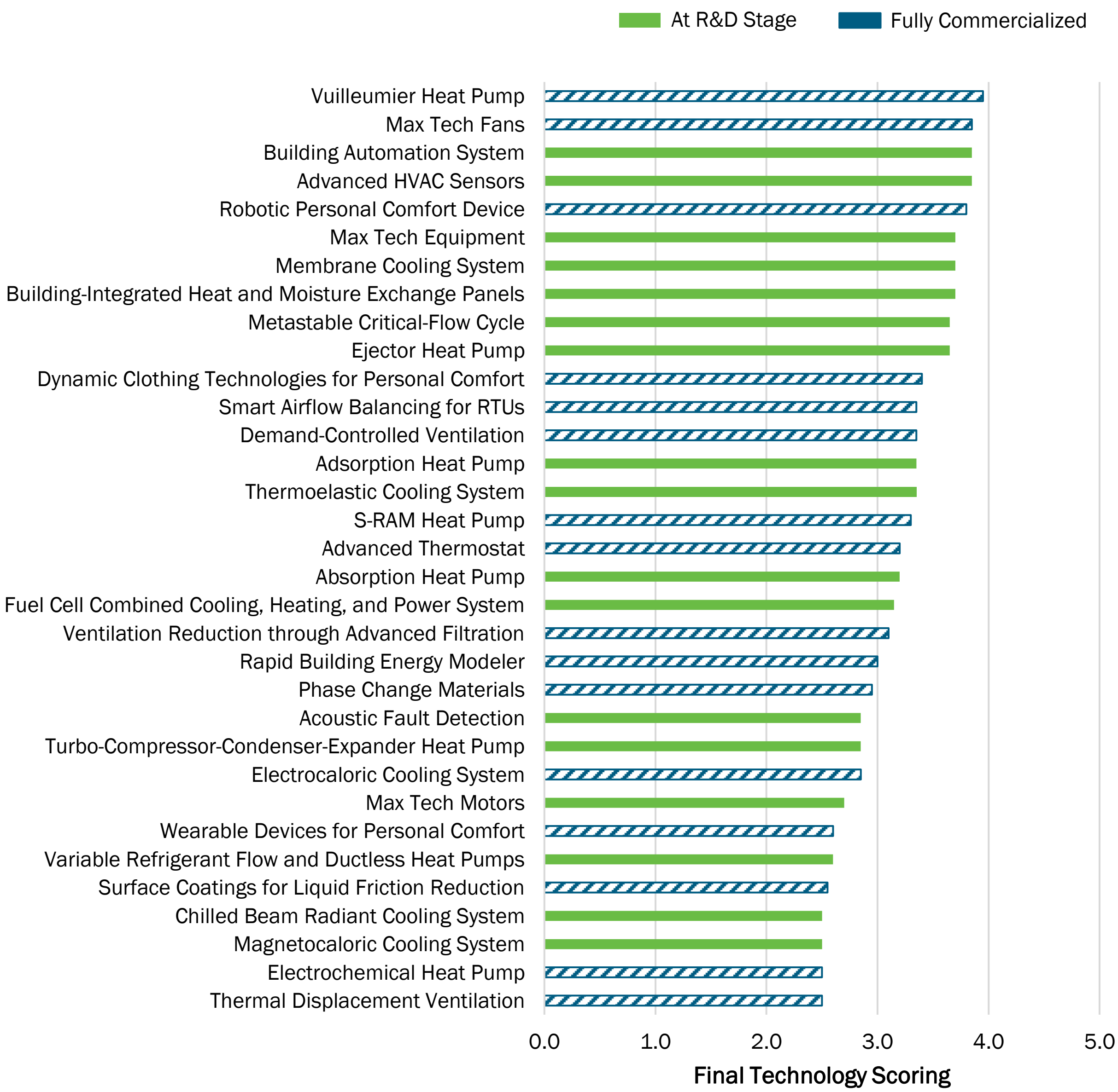

Figure 9: Final ranking of high priority technology options

2.6 In-Depth Research and Analysis

We then developed a detailed profile of each of the 18 high priority technology options, which included the key elements outlined in Table 7. These profiles provide an overview of the technology, its current development status, key R&D efforts, projections of performance and energy savings, and other attributes that may affect its market uptake. For the 66 technologies screened out during the scoring process we prepared a brief summary, which is contained in Appendices B and C.

Table 7: Key Subsections of the High Priority Technology Option Profiles

Profile Subsections	Description
Summary Table	Brief description of the technology option, the estimated technical energy-savings potential, technical maturity, projected cost/complexity, and other attributes.
Technology Description	How the technology works, its practical uses, its limitations, and why the technology offers an efficiency improvement over conventional technologies, including an image or schematic where available.
Technology Maturity and Current Development Status	Estimated TRL status of the technology, along with a summary of key R&D efforts and commercialization partners.
Barriers to Market Adoption	Summary of technical, market, policy, and other barriers that may limit the technology's adoption once fully developed. Note: Many early-stage technologies have obvious performance, cost, and other barriers that require R&D support to overcome; therefore, in this section we assumed successful R&D and demonstration, focusing on other barriers instead.
Potential Market and Replacement Applications	List of the target applications for the technology (e.g., commercial building segments, HVAC equipment types, climate zones).
Energy Savings	Summary of demonstrated performance and energy savings in laboratory or field testing, including researcher projections for early-stage technologies.
Cost and Complexity	Projections of the incremental first cost of the technology option and the incremental complexity associated with its installation, operation, and maintenance.
Peak-Demand Reduction and Other Non-Energy Benefits	Summary of the technology's benefits beyond energy savings, including but not limited to: peak electrical demand reduction potential, decreased direct GWP impact, improved comfort, improved IAQ, simplified maintenance, and reduced noise/vibration.
Next Steps for Technology Development	Recommended RD&D activities to advance the technology toward market introduction (or greater adoption) and more energy savings.

3 Summary of High Priority Technology Options

This section summarizes the 18 high priority technology options and details their technical energy savings potential. The sections of the report immediately following (Section 4 through Section 7) provide detailed profiles of each technology option, and are organized into the following categories:

- **Technology Enhancements for Current Systems** improve the performance and energy efficiency of current generation of HVAC equipment and systems.
- **Alternative Electrically Driven Heat Pump Technologies** use electricity as their primary energy input. They use advanced technologies (either vapor-compression or non-vapor-compression) to provide heating or cooling more efficiently.
- **Alternative Gas-Fired Heat Pump Technologies** provide heating or cooling more efficiently, using a thermally activated heat pump cycle, and use natural gas as the primary energy input.
- **Alternative System Architectures** provide localized comfort to building occupants to reduce the operating requirements of traditional HVAC systems.

Table 8 provides a summary of the high priority technology options in each category.

Table 8: High Priority Technology Options by Category

Technology Category	Technology Option	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Technology Enhancements for Current Systems	Advanced HVAC Sensors	Late Stage Development (TRL 7-8)	0.63	3.85
	Building-Integrated Heat and Moisture Exchange Panels	Late Stage Development (TRL 7-8)	0.53	3.70
	Ventilation Reduction through Advanced Filtration	Late Stage Development (TRL 7-8)	0.25	3.10
	Surface Coatings for Liquid Friction Reduction	Technology Demonstration (TRL 5-6)	0.12	2.55
Alternative Electrically Driven Heat Pump Technologies	Membrane Cooling System	Technology Demonstration (TRL 5-6)	0.51	3.70
	Metastable Critical-Flow Cycle	Technology Development (TRL 3-4)	0.45	3.65
	Thermoelastic Cooling System	Technology Development (TRL 3-4)	0.41	3.35
	S-RAM Heat Pump	Technology Development (TRL 3-4)	0.25	3.30
	Turbo-Compressor-Condenser-Expander Heat Pump	Technology Development (TRL 3-4)	0.31	2.85
	Electrocaloric Cooling System	Early Stage Research (TRL 1-2)	0.26	2.85
	Electrochemical Heat Pump	Technology Development (TRL 3-4)	0.21	2.50
	Magnetocaloric Cooling System	Technology Development (TRL 3-4)	0.21	2.50
Alternative Gas-Fired Heat Pump Technologies	Vuilleumier Heat Pump	Technology Development (TRL 3-4)	0.84	3.95
	Ejector Heat Pump	Technology Development (TRL 3-4)	1.01	3.65
	Fuel Cell Combined Cooling, Heating, and Power System	Technology Demonstration (TRL 5-6)	0.37	3.15
Alternative System Architectures	Robotic Personal Comfort Device	Technology Demonstration (TRL 5-6)	0.53	3.80
	Dynamic Clothing Technologies for Personal Comfort	Technology Development (TRL 3-4)	0.53	3.40
	Wearable Devices for Personal Comfort	Technology Demonstration (TRL 5-6)	0.35	2.60

3.1 Technology Enhancements for Current Systems

Table 9 provides a brief description and final ranking of the high priority technology options within the Technology Enhancements for Current Systems category, plus their final ranking. Section 4 provides detailed profiles of each of the priority technology options in this category.

Table 9: Brief Descriptions of Technology Enhancements for Current Systems

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Advanced HVAC Sensors (4.1)	The next generation of sensors will incorporate features such as wireless communication, low-energy computing, energy harvesting technologies, and advanced manufacturing processes, to enable advanced building controls at lower cost.	Late Stage Development (TRL 7-8)	0.63	3.85
Building-Integrated Heat and Moisture Exchange Panels (4.2)	Modular systems installed within the building envelope to precondition ventilation air by transfer of thermal energy from exhaust air, thus decreasing overall energy consumption.	Late Stage Development (TRL 7-8)	0.53	3.70
Ventilation Reduction through Advanced Filtration (4.3)	Specialized adsorbent filters capture CO_2 and other contaminants from the return airstream, which allows purified air to recirculate throughout the building and reduces the amount of outside air required.	Late Stage Development (TRL 7-8)	0.25	3.10
Surface Coatings for Liquid Friction Reduction (4.4)	Advanced surface coatings repel water and other contaminants from heat exchanger coils, reducing fouling and frost build up.	Technology Demonstration (TRL 5-6)	0.12	2.55

3.2 Alternative Electrically Driven Heat Pump Technologies

Table 10 provides a brief description of the high priority technology options within the Alternative Electrically Driven Heat Pump Technologies category, plus their final ranking. Section 4 provides detailed profiles of each of the priority technology options in this category.

Table 10: Brief Descriptions for Alternative Electrically Driven Heat Pump Technologies

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Membrane Cooling System (5.1)	Systems using specialized polymer membranes to transfer water across several assemblies that enable efficient dehumidification and evaporative cooling.	Technology Demonstration (TRL 5-6)	0.51	3.70
Metastable Critical-Flow Cycle (5.2)	A novel cooling cycle that uses a specialized converging-diverging nozzle to expand a high-pressure refrigerant, which decreases temperature as it evaporates supersonically.	Technology Development (TRL 3-4)	0.45	3.65
Thermoelastic Cooling System (5.3)	Systems that transfer heat by cyclically applying physical stress to a specialized elastocaloric (shape memory alloy, or SMA) material that changes temperature when compressed and released.	Technology Development (TRL 3-4)	0.41	3.35
S-RAM Heat Pump (5.4)	A system that uses double-ended pistons to couple the compression and expansion processes of a vapor-compression cycle, achieving higher efficiencies.	Technology Development (TRL 3-4)	0.25	3.30
Turbo-Compressor-Condenser-Expander Heat Pump (5.5)	A system that combines multiple vapor compression components into a joint assembly operating on a common shaft for improved work recovery and energy efficiency.	Technology Development (TRL 3-4)	0.31	2.85
Electrocaloric Cooling System (5.6)	Specialized electrocaloric materials are oscillated in an electric field, which causes them to experience reversible temperature change and transfer heat.	Early Stage Research (TRL 1-2)	0.26	2.85
Electrochemical Heat Pump (5.7)	An electrochemical cell using a proton exchange membrane compresses a hydrogen working fluid to drive a vapor-compression or metal-hydride heat pump cycle.	Technology Development (TRL 3-4)	0.21	2.50
Magnetocaloric Cooling System (5.8)	A system in which specialized magnetocaloric materials are cyclically exposed to a changing magnetic field, creating a reversible temperature change in the material that drives the cooling cycle.	Technology Development (TRL 3-4)	0.21	2.50

3.3 Alternative Gas-Fired Heat Pump Technologies

Table 11 provides a brief description of the high priority technology options within the Alternative Gas-Fired Heat Pump Technologies category, plus their final ranking. Section 6 provides detailed profiles of each of the priority technology options in this category.

Table 11: Brief Descriptions for Alternative Gas-Fired Heat Pump Technologies

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Vuilleumier Heat Pump (6.1)	The system uses a gas-fired heat engine to operate a cylinder assembly that compresses and expands a refrigerant within several chambers, transferring heat with hydronic loops in the building.	Technology Development (TRL 3-4)	0.84	3.95
Ejector Heat Pump (6.2)	Specially designed nozzles drive a heat pump cycle by transferring energy from a high-pressure motive fluid to a secondary refrigerant.	Technology Development (TRL 3-4)	1.01	3.65
Fuel Cell Combined Cooling, Heating, and Power System (6.3)	The packaged system provides both space cooling and electric power to buildings by utilizing the waste heat from a natural gas fuel cell to operate an evaporative liquid-desiccant cooling cycle.	Technology Demonstration (TRL 5-6)	0.37	3.15

3.4 Alternative System Architectures

Table 12 provides a brief description of the high priority technology options within the Alternative System Architectures category, plus their final ranking. Section 6 provides detailed profiles of each of the priority technology options in this category.

Table 12: Brief Descriptions for Alternative System Architectures

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Robotic Personal Comfort Device (7.1)	A miniaturized heat pump on a motorized base that provides localized space heating and cooling for building occupants as they travel around the building.	Technology Demonstration (TRL 5-6)	0.53	3.80
Dynamic Clothing Technologies for Personal Comfort (7.2)	Advanced materials and fabrics that reject or trap heat more efficiently than other materials, so that building occupants require less thermal comfort from the HVAC system.	Technology Development (TRL 3-4)	0.53	3.40
Wearable Devices for Personal Comfort (7.3)	Wearable devices, furniture, and other innovations that provide personalized comfort to building occupants, using small-scale heating and cooling elements.	Technology Demonstration (TRL 5-6)	0.35	2.60

4 Technology Enhancements for Current Systems

Technology Enhancements for Current Systems improve the performance and energy efficiency of current generation of HVAC equipment and systems. Table 13 provides a brief description and final ranking for the selected high priority technology options within the Technology Enhancements for Current Systems category.

Table 13: Brief Descriptions of Technology Enhancements for Current Systems

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Advanced HVAC Sensors (4.1)	The next generation of sensors will incorporate features such as wireless communication, low-energy computing, energy harvesting technologies, and advanced manufacturing processes, to enable advanced building controls at lower cost.	Late Stage Development (TRL 7-8)	0.63	3.85
Building-Integrated Heat and Moisture Exchange Panels (4.2)	Modular systems installed within the building envelope to precondition ventilation air by transfer of thermal energy from exhaust air, thus decreasing overall energy consumption.	Late Stage Development (TRL 7-8)	0.53	3.70
Ventilation Reduction through Advanced Filtration (4.3)	Specialized adsorbent filters capture CO_2 and other contaminants from the return airstream, which allows purified air to recirculate throughout the building and reduces the amount of outside air required.	Late Stage Development (TRL 7-8)	0.25	3.10
Surface Coatings for Liquid Friction Reduction (4.4)	Advanced surface coatings repel water and other contaminants from heat exchanger coils, reducing fouling and frost build up.	Technology Demonstration (TRL 5-6)	0.12	2.55

4.1 Advanced HVAC Sensors

Brief Description	The next generation of sensors will incorporate features such as wireless communication, low-energy computing, energy harvesting technologies, and advanced manufacturing processes, to enable advanced building controls at lower cost.

Technology Characteristics	Value	Comments
Technology Category	Technology Enhancements for Current Systems	
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)	Some sensor technologies are being tested in field demonstrations and entering the marketplace, while others are in laboratory R&D phases
Unit Energy Savings	18%	Sensors themselves do not save energy, but can enable occupancy-based control and other strategies
Technical Energy Savings Potential	670.4 TBtu	All commercial HVAC energy consumption
Non-Energy Benefits	Potential for significant benefits, but not well documented	Potential for improved comfort and operational performance of the building
Peak Demand Reduction Potential	Low	Could help in identification of peak-demand reduction opportunities, as well as implementation of demand response (DR)
Relative Cost Premium	Moderately higher upfront cost	Anticipated to have moderately higher cost initially compared to current sensors, but will offer opportunities for small commercial and retrofit applications that were cost prohibitive previously
Operational Complexity	Neutral	Commercial sensor systems are designed with low installation and operational complexity, despite the greater number of nodes

Background

Technology Description

Commercial building HVAC systems use a variety of sensors to monitor conditions within a building, which generally provide input into the building control system as well. Traditionally, the systems rely on the temperature and humidity sensors present in a thermostat to determine whether the current status meets pre-set comfort settings, and to make any changes to the amount of space cooling, space heating, or ventilation provided to the space. Small commercial buildings will typically have one thermostat for each HVAC system (e.g., one per RTU), whereas larger buildings will have sensors deployed across each zone to feed information into the central energy management system (EMS) to control whole-building HVAC systems (such as chillers). The current generation of sensors can operate equipment effectively, but require costly wired connections and cannot account for the changing dynamics of the building, such as occupancy.

Advances in wireless communications and computing technologies offer significant potential to enhance the capabilities of sensor networks for commercial HVAC applications. Figure 10 shows examples of several multifunction, plug-and-play wireless sensors under development. Beyond using improved sensors, these systems incorporate wireless communications, low-energy computing, energy harvesting technologies, and advanced manufacturing processes. These features reduce installation cost and complexity, and allow for increased deployment across the commercial buildings space.

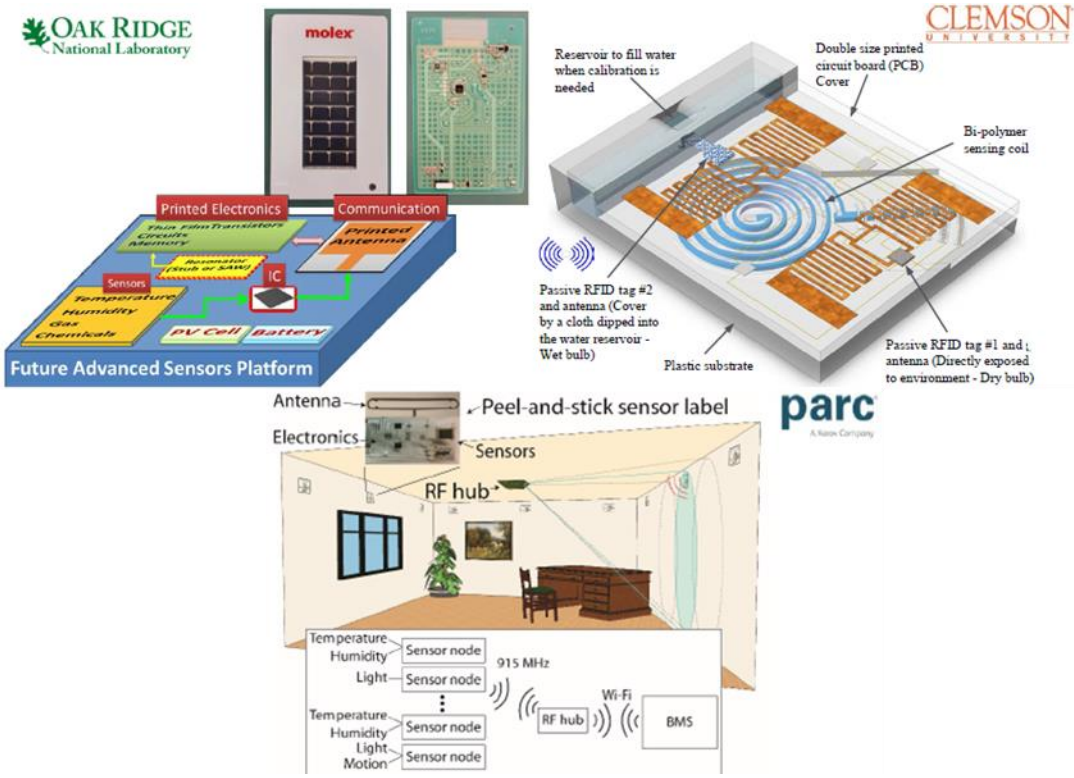

Figure 10: Examples of multifunction plug-and-play wireless sensors

Source: Sofos (2017)[15]

These sensor technologies provide energy savings by improving the control of commercial buildings, through occupancy sensing, automatic setpoint scheduling, and other strategies. For example, sensors can determine the number of occupants within a room to adjust ventilation rates, and they allow the control system to relax the temperature setpoint once the occupants leave. While these features are available for larger buildings with EMS, small and older commercial buildings often cannot incorporate these strategies cost-effectively. In addition, wider sensor networks can enable other energy-saving strategies like lighting controls, or non-energy benefits such as occupant mapping for building safety, security, and space utilization.

Technical Maturity and Current Developmental Status

Building control and sensor vendors continue to improve their product offerings, with many incorporating wireless technologies and advanced control schemes for new buildings and major renovations. Depending on the building type and application, certain commercial building codes now require CO_2 monitoring, or other

[15] Sofos, Marina. 2017. "Building Technologies Office (BTO) Sensor and Control Technologies R&D Program Overview." 2017 BTO Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/10_Sofos%2C%20Marina_Sensors%20and%20Controls.pdf

sensing, to adjust ventilation systems (demand-controlled ventilation, or DCV).[16] Some codes require occupancy-based lighting controls,[17] again as a function of building type and usage.

DOE BTO has funded several research projects looking to support development of the next generation of low-cost HVAC sensors, especially for small commercial buildings and retrofits. Table 14 highlights several research efforts underway. In addition, ARPA-e held a workshop in July 2016 to explore opportunities for advanced occupancy sensors,[18] and is currently soliciting proposals for funding under the Saving Energy nationwide in Structures with Occupancy Recognition (SENSORS) program.[19]

Table 14: Examples of Advanced HVAC Sensors Under Development

Research Organization	Technology Name	Brief Description
PNNL	Retro-commissioning Sensor Suitcase	System of sensors, data loggers, and analysis software that monitor building performance over several weeks to allow building owners or contractors to quickly identify low-cost energy efficiency measures.[20]
NREL	Image Processing Occupancy Sensor (IPOS)	Specialized sensor that combines an inexpensive smartphone camera with advanced imaging algorithms for better identification of sedentary and active occupants in buildings.[21]
ORNL	Multifunctional Sensor Platform	Wireless sensor platform involving an energy harvesting power source, low-cost manufacturing, peel-and-stick installation, integrated design, and multifunctional performance.[22]
Intelligent Optical Systems Inc.	Optical Humidity Sensors	Luminescence-based optical sensors to measure humidity levels within buildings, for monitoring IAQ. Target performance is to improve stability and resistance to airborne contaminants, while maintaining a competitive cost.[23]
Dioxide Materials	Whole-Building Carbon Dioxide Monitoring	Advanced electrochemical CO_2 sensors with low cost and low energy requirements, which allows for improved demand controlled ventilation (DCV) capabilities in a building by increasing the number of wireless sensing nodes.[24]

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[16] PNNL. 2012. "Demand Control Ventilation." August 2012. Available at: https://www.energycodes.gov/sites/default/files/documents/cn_demand_control_ventilation.pdf

[17] Baumgartle, Brian. 2014. "Lighting Control Requirements: What's Current and What to Expect." Consulting-Specifying Engineer. January 2014. Available at: https://www.csemag.com/single-article/lighting-control-requirements-what-s-current-and-what-to-expect/0ec0a9a12ebf85a4c998c79c67095d6a.html

[18] ARPA-e. 2016. "Advanced Occupancy Sensors for Better Buildings Workshop." July 2016. Available at: https://arpa-e.energy.gov/?q=workshop/advanced-occupancy-sensors-better-buildings-workshop

[19] ARPA-e. 2017. "DE-FOA-0001737: Saving Energy Nationwide in Structures with Occupancy Recognition (SENSOR)." July 2017. Available at: https://arpa-e-foa.energy.gov/#FoaId2d3f7530-bdc3-4090-ae7c-0d5ca8584e07

[20] PNNL. 2015. "Retro-commissioning Sensor Suitcase." January 2015. Available at: https://energy.gov/sites/prod/files/2015/01/f19/Sensor_Suitcase2.pdf

[21] Gentile Polese, Luigi. 2012. "IPOS Image Processing Occupancy Sensor." NREL. November 2012. Available at: https://techportal.eere.energy.gov/techpdfs/IPOS%201-pager%20promo%20v2.pdf

[22] Joshi, Pooran. 2016. "Low-cost Manufacturing of Wireless Sensors for Building Monitoring Applications." ORNL. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/32611_Kuruganti_040616-1405.pdf

[23] DOE. 2017. "Optical Humidity Sensors for Building Energy Performance and Air Quality Control." Accessed August 2017. Available at: https://energy.gov/eere/buildings/downloads/optical-humidity-sensors-building-energy-performance-and-air-quality

[24] DOE. 2017. "Low-Cost, High-Accuracy, Whole-Building Carbon Dioxide Monitoring for Demand Control Ventilation." Accessed August 2017. Available at: https://energy.gov/eere/buildings/downloads/low-cost-high-accuracy-whole-building-carbon-dioxide-monitoring-demand

Barriers to Market Adoption

In addition to continuing with technology development, advanced HVAC sensor systems must overcome the same challenges facing conventional technologies: provide low-cost installation and integration, be scalable across building and system types, and be interoperable, user-friendly, maintenance-free, and highly accurate.[25] The technologies can only succeed if their operational complexities (e.g., battery replacement) outweigh their performance improvements over today's relatively simple sensors.

Energy Savings Potential

Potential Market and Replacement Applications

These sensors would be applicable for all HVAC consumption for all commercial buildings. As noted previously, advanced HVAC sensors would improve the capabilities offered by EMS systems in new commercial buildings. The systems are designed for simplified installation in retrofit applications (e.g., by being wireless and self-powered).

Energy Savings

Sensors themselves do not provide energy savings, but rather allow for improved control of the building's HVAC system to match occupant comfort and/or operational requirements. A 2013 PNNL building modelling study found that advanced occupancy sensors and controls could save an average of 18% of the HVAC energy across U.S. commercial buildings.[26] Other researchers estimate 20-30% savings or more for sensors' impacts on whole-building energy consumption, including lighting and other end-uses.[27]

Cost and Complexity

Advanced HVAC sensor systems will be designed to have lower cost and complexity of installation and operation, by incorporating wireless communications, self-commissioning, energy harvesting, and other capabilities. Researchers being supported by current DOE BTO programs have a cost target of one to several hundred dollars per sensor node,[28] while some have targets around ten dollars.[29] The ARPA-e program targets $0.08/sq.ft., or less, for advanced sensor technologies ($1,200 cost for a 15,000 sq.ft. building).[30]

Peak-Demand Reduction and Other Non-Energy Benefits

Advanced sensors will provide greater comfort for building occupants by giving control systems greater visibility into occupancy and local temperature, humidity, and IAQ conditions. In addition, the sensors could provide information that supports safety and security activities, as well as improvements in space utilization.

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[25] Sofos, Marina. 2017. "Building Technologies Office (BTO) Sensor and Control Technologies R&D Program Overview." 2017 BTO Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/10_Sofos%2C%20Marina_Sensors%20and%20Controls.pdf

[26] Zhang et al. 2013. "Energy Savings for Occupancy-Based Control (OBC) of Variable Air-Volume (VAV) Systems." PNNL. January 2013. Available at: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22072.pdf

[27] Joshi, Pooran. 2016. "Low-cost Manufacturing of Wireless Sensors for Building Monitoring Applications." ORNL. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/32611_Kuruganti_040616-1405.pdf

[28] Sofos, Marina. 2017. "Building Technologies Office (BTO) Sensor and Control Technologies R&D Program Overview." 2017 BTO Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/10_Sofos%2C%20Marina_Sensors%20and%20Controls.pdf

[29] Joshi, Pooran. 2016. "Low-cost Manufacturing of Wireless Sensors for Building Monitoring Applications." ORNL. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/32611_Kuruganti_040616-1405.pdf

[30] ARPA-e. 2017. "DE-FOA-0001737: Saving Energy Nationwide in Structures with Occupancy Recognition (SENSOR)." July 2017. Available at: https://arpa-e-foa.energy.gov/#FoaId2d3f7530-bdc3-4090-ae7c-0d5ca8584e07

Through greater insight into building operations provided by advanced HVAC sensors, building operators should be better able to reduce peak electricity demand and identify DR opportunities. However, these capabilities require additional development work.

Next Steps for Technology Development

Commercial HVAC systems can greatly benefit from increased deployment of temperature, occupancy, and other sensors throughout the building, particularly for small commercial buildings and retrofits. Nevertheless, additional research is necessary to bring these technologies to market and demonstrate their capabilities. Despite their shortcomings, current HVAC controls are relatively robust, and new sensor technologies must meet the reliability and other operational criteria expected by building operators.

Table 15 lists potential next steps to advance HVAC sensors.

Table 15: Recommended Next Steps for the Development of Advanced HVAC Sensors

Activities
Continue to develop low-cost, wireless sensor technologies and systems for commercial HVAC systems
Conduct laboratory testing and field demonstrations to evaluate their effectiveness relative to conventional HVAC sensors and control strategies
Work with controls and EMS vendors to integrate advanced HVAC sensors into product and service offerings

4.2 Building-Integrated Heat and Moisture Exchange Panels

Brief Description	Modular systems installed within the building envelope to precondition ventilation air by transfer of thermal energy from exhaust air, thus decreasing overall energy consumption.

Technology Characteristics	Value	Comments
Technology Category	Technology Enhancements for Current Systems	
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)	Final product development and early commercialization
Unit Energy Savings	35%	Estimated HVAC energy savings from heat recovery
Technical Energy Savings Potential	419.0 TBtu	Assumes HVAC energy consumption for large office, assembly, and education buildings as target markets
Non-Energy Benefits	Potential for significant benefits, but not well documented	Potential for increased IAQ by placing outside air sources closer to occupants, as well as a reduced requirement for HVAC system capacity and equipment
Peak Demand Reduction Potential	Medium	Peak-demand reduction would be as expected for the average level of energy savings
Relative Cost Premium	Moderately higher upfront cost	Potential for comparable upfront cost when including equipment downsizing, but requires building envelope redesign
Operational Complexity	Moderately higher complexity	Not suitable for all building types or applications, due to the need for building envelope interaction for each major zone or room

Background

Technology Description

HVAC system designers incorporate heat recovery ventilators (HRVs, which recover only sensible heat) and energy recovery ventilators (ERVs, which recover both sensible and latent heat) as part of packaged RTUs and DOASs to increase the energy efficiency of buildings. These technologies precondition the outside air entering the building by transferring thermal energy from already-conditioned exhaust air. For example, an ERV system will transfer heat from stale indoor air to preheat cold air from outside during winter, reducing the energy consumption needed to bring the outside ventilation air to proper indoor conditions. These heat recovery systems are increasingly part of both high-performance building specifications and, for many parts of the U.S., baseline codes.

The start-up company Architectural Applications has developed a modular ERV panel designed for installation in the building envelope to provide preconditioned outside air directly to a room. Figure 11 provides an illustration of the building-integrated heat & moisture exchange (BIHME) panels. The insulated panels are installed as part of the building's curtainwall or cladding and consist of a membrane-based air-to-air heat and moisture exchanger that transfers sensible and latent heat from within the building to precondition outside air. Each panel uses two small fans to generate up to 200 CFM of supply and exhaust airflow, serving approximately 2,500 sq.ft. of office space.[31] In some cases, the technology will allow system designers to downsize conventional building HVAC equipment pertaining to outside air supply, including ductwork and other related components. The actual downsizing benefit will depend on the building's climate and other design considerations.

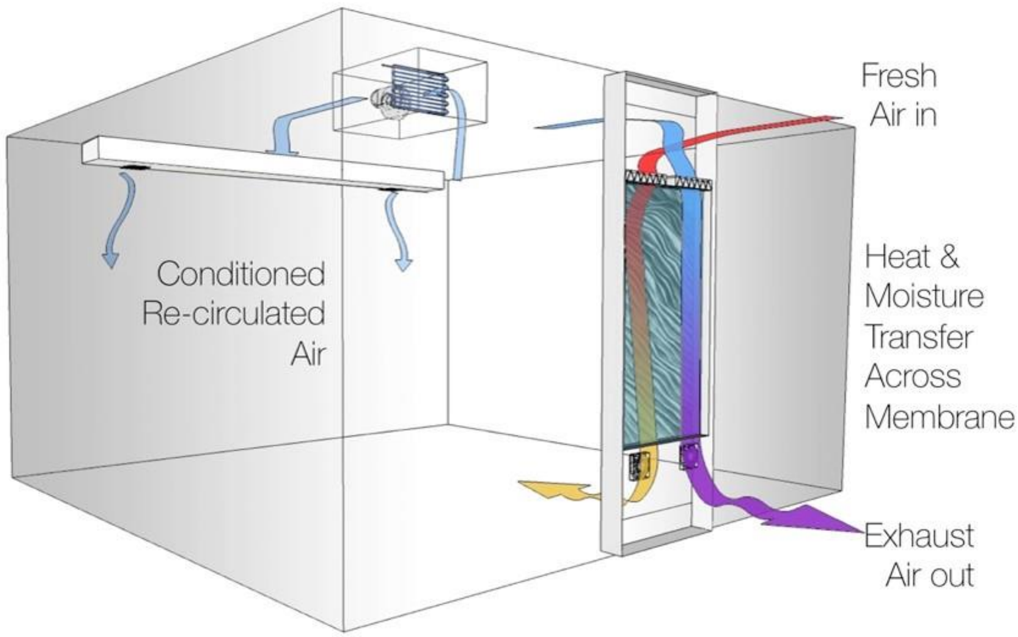

Figure 11: Building-integrated heat and moisture exchange panels

Source: Architectural Applications (2017)[32]

Technical Maturity and Current Developmental Status

Architectural Applications (A2) has recently commercialized their BIHME product as AirFlow™ Panels. The company developed the product with LBNL and other partners via several projects funded by BTO and ARPA-e, and is currently improving the manufacturability and production capability for widespread launch.[33]

[31] Architectural Applications. 2016. "AirFlow Panels CW-Series." June 2016. Available at: https://static1.squarespace.com/static/53ced83fe4b0435504e2e141/t/576ae17e579fb36f7edffc47/1466622335845/20160617+AFP+Tech+Manual.pdf

[32] Breshears and Duncan. 2017. "AirFlow Panels – Get More from Your Building." Architectural Applications. January 2017. Available at: https://www.slideshare.net/jbreshears/airflowtm-panels-get-more-form-your-building

[33] Breshears, John. 2016. "Building-Integrated Heat & Moisture Exchange." Architectural Applications. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/30004_Breshears_040716-1015.pdf

Barriers to Market Adoption

The technology could be cost-competitive with conventional ERV systems for new construction and major renovation projects, where the product's cost can be offset by the reduced size of HVAC equipment and ductwork, as well as savings on building cladding. Nevertheless, the BIHME panels will present challenges for existing buildings because of the need for building envelope changes. In addition, the technology requires greater coordination between contractors who work with the building envelope and those who focus on HVAC, who traditionally do not have much interaction.

Energy Savings Potential

Potential Market and Replacement Applications

This technology may be suitable for a wide variety of commercial buildings, but target applications would be HVAC systems for large office, assembly, and education buildings.

Energy Savings

Architectural Applications claims the BIHME panels could reduce 25-50% of A/C energy consumption and allow HVAC system downsizing by 7-10%.[34] The technology could provide energy savings beyond traditional ERVs by separating the space conditioning duties of outside air and recirculating air; lowering the pressure drop across the ERV for reduced fan consumption; and delivering outside air directly into the room or zone, rather than through the building's ductwork. Nevertheless, the available laboratory and field testing results focus on product capabilities rather than a direct performance comparison relative to traditional heat recovery systems. We conservatively estimate a total of 35% HVAC energy savings, based on latest information from the BTO project.[35]

Cost and Complexity

As noted above, the technology requires changes to the building envelope, which are typically only cost-effective during new construction and major retrofits. Nevertheless, BIHME panels are predicted to be cost-competitive against traditional systems for target applications, once HVAC downsizing and building envelope material savings are captured.[36]

Peak-Demand Reduction and Other Non-Energy Benefits

Similar to ERVs, the technology is expected to offer peak-demand savings by preconditioning outside air during peak days, with the percentage reduction in line with energy savings. In addition, placing outside air sources closer to occupants could increase IAQ.

Next Steps for Technology Development

BIHME panels are a unique combination of HVAC and building envelope technologies, and are particularly suited for high performance new buildings where the cost impacts can be mitigated. The technology will

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[34] Architectural Applications. 2016. "AirFlow Panels CW-Series." June 2016. Available at: https://static1.squarespace.com/static/53ced83fe4b0435504e2e141/t/576ae17e579fb36f7edffc47/1466622335845/20160617+AFP+Tech+Manual.pdf

[35] Breshears, John. 2016. "Building-Integrated Heat & Moisture Exchange." Architectural Applications. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/30004_Breshears_040716-1015.pdf

[36] Architectural Applications. 2016. "AirFlow Panels CW-Series." June 2016. Available at: https://static1.squarespace.com/static/53ced83fe4b0435504e2e141/t/576ae17e579fb36f7edffc47/1466622335845/20160617+AFP+Tech+Manual.pdf

Breshears, John. 2016. "Building-Integrated Heat & Moisture Exchange." Architectural Applications. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/30004_Breshears_040716-1015.pdf compete with several other heat recovery and HVAC design strategies, and more research is necessary to determine how BIHME panels compare to traditional DOAS and ERV designs.

Table 16 lists potential next steps to advance building-integrated heat and moisture exchange panels.

Table 16: Recommended Next Steps for the Development of Building-Integrated Heat and Moisture Exchange Panels

Activities
Conduct modeling research to compare the expected performance of BIHME panels to other heat recovery and HVAC system designs
Conduct field demonstrations at pilot sites to understand long-term performance and acquire occupant feedback regarding the BIHME panels
Develop partnerships with leading architectural and engineering firms to demonstrate the BIHME panels on showcase projects

4.3 Ventilation Reduction through Advanced Filtration

Brief Description	Specialized adsorbent filters capture CO_2 and other contaminants from the return airstream, which allows purified air to recirculate throughout the building and reduces the amount of outside air required.

Technology Characteristics	Value	Comments
Technology Category	Technology Enhancements for Current Systems	
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)	Products are currently available for select applications. Several demonstration field studies underway.
Unit Energy Savings	20%	Estimated 20% annual energy savings or greater based on reduced outside air requirements
Technical Energy Savings Potential	191 TBtu	HVAC consumption for all building types except small offices
Non-Energy Benefits	Potential for significant benefits, but not well documented	Improved IAQ by closely measuring and directly removing indoor contaminants
Peak Demand Reduction Potential	High	Outside air systems have disproportionately high energy consumption on peak demand days – outside air refresh cycles can be scheduled around peak electricity pricing
Relative Cost Premium	Neutral	The technology itself has higher cost, but offers the potential for equipment downsizing
Operational Complexity	Neutral	Systems require annual replacement of cartridges, sensor calibration, and other maintenance tasks

Background

Technology Description

Traditional ventilation systems bring in outside air and expel exhaust air to maintain proper IAQ within the building. For most systems, the amount of airflow entering and exiting the building is based on accepted guidelines from ASHRAE 62.1 and other building codes that specify an airflow rate based on the building area (rate per sq. ft.) or the expected number of occupants (rate per person). Because outside air usually requires sensible and latent heat adjustments to meet proper indoor temperatures, conditioning of outside air makes up a considerable amount of the building's HVAC energy load. In recent years, demand controlled ventilation (DCV) controls incorporate occupancy sensors (infrared, CO_2, etc.) to decrease the amount of outside air sent to specific zones during periods of low or no occupancy (e.g., unoccupied conference rooms). Nevertheless, this strategy requires substantial outside air conditioning to maintain IAQ.

This traditional dilution/exhaust ventilation method maintains IAQ, but it does not typically measure or capture contaminants directly (e.g., CO_2 or volatile organic compounds (VOCs)). Researchers at EnVerid have developed specialized adsorbent filters to capture CO_2 and other contaminants from the return airstream and exhaust them from the building (see Figure 12). The purified air can recirculate throughout the building, reducing the outside air requirement by 80% or more. Less outside air results in lower energy consumption to condition the air to comfortable temperatures. EnVerid estimates 20-40% HVAC energy savings for large commercial and industrial buildings and has shown these results in DOE and GSA field studies.[37]

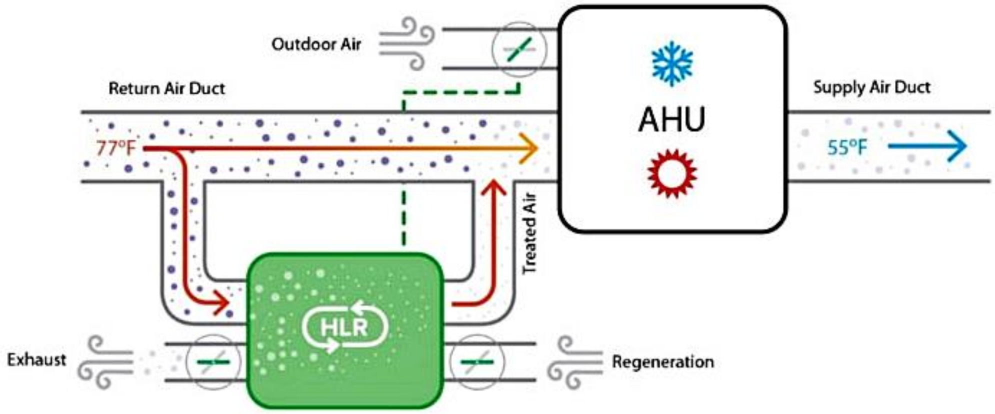

Figure 12: Schematic of ventilation reduction through advanced filtration

Source: EnVerid (2017)[38]

Figure 13 provides a cutaway view of EnVerid's HVAC Load Reduction product. The system passes indoor air through a bank of contaminant storage cartridges, which use a sorbent to remove contaminants from the indoor air stream. These include carbon dioxide, formaldehyde, and VOCs. Outdoor air may also contain undesirable components; the EnVerid product reduces their intake by requiring less air from outside the building. The system uses sensors to monitor IAQ levels and adjust the amount of air entering the building. Several times a day, the system enters a regeneration phase where slightly heated air flows over the sorbent material, releasing the contaminants into an airstream that is diverted to the outdoors. The system is designed to operate in parallel with traditional ventilation systems. Maintenance includes annual cartridge replacement and sensor calibration.

[37] EnVerid Website. Accessed August 2017. Available at: http://www.enverid.com/projects
[38] EnVerid Website. Accessed August 2017. Available at: http://www.enverid.com/sites/default/files/pdf/enVeridHLR1000e-productR6_0.pdf

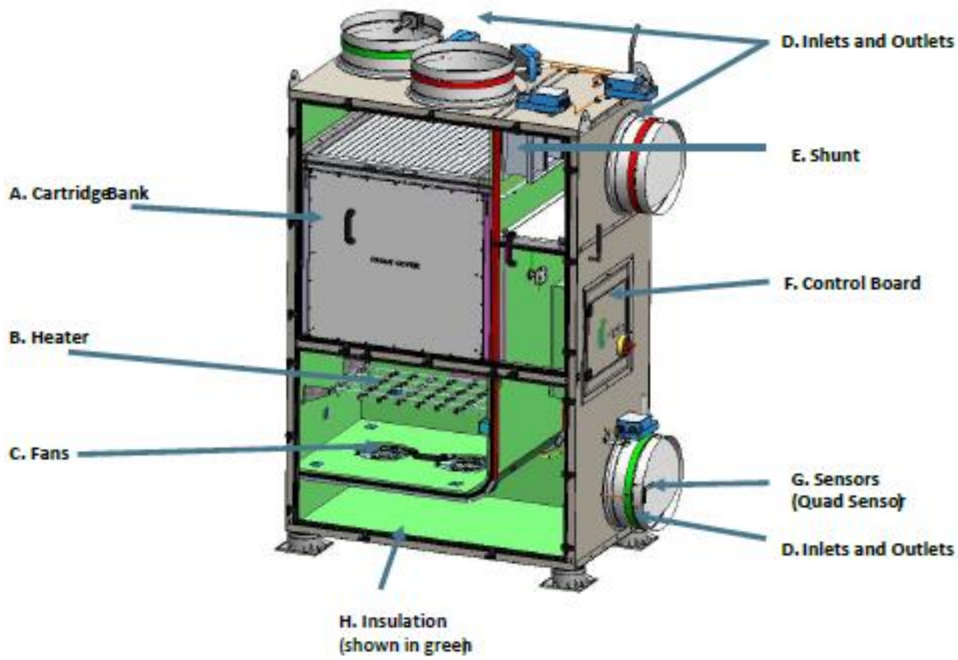

Figure 13: Cutaway view of York EcoAdvance 100E

Source: York (2016)[39]

Technical Maturity and Current Developmental Status

The technology is commercially available in the U.S. and globally. EnVerid is conducting field studies with the DOE[40] and GSA,[41] and has partnered with JCI/York to market the products to HVAC contractors, architecture & engineering firms, and building owners. The technology is approved for use under ASHRAE 62.1 through the IAQP ventilation methodology, where the airflow rate is controlled by measuring the key contaminants of interest.[42]

Barriers to Market Adoption

Substantially decreasing the amount of outside air through use of advanced filters represents a significant change in the building industry. The largest barrier to market adoption is acceptance by building code jurisdictions, HVAC system designers, and customers. While most jurisdictions use ASHRAE 62.1 as the basis for state and local building codes, not every building code agency adopts ASHRAE 62.1 fully or has familiarity with the newer IAQP methodology. Cost and payback are also key issues in moderate climates where the space conditioning loads for outside air are lower than more extreme climates.

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[39] York. 2016. "EcoAdvance HVAC Load Reduction Module." December 2016. Available at: http://www.york.com/for-your-workplace/air-systems/hvac-load-reduction/ecoadvance-hlr

[40] DOE. 2017. "enVerid Systems - HVAC Load Reduction." Accessed August 2017. Available at: https://energy.gov/eere/buildings/downloads/enverid-systems-hvac-load-reduction

[41] GSA. 2017. "Smart Scrubbers for HVAC Load Reduction." August 2017. Available at: https://www.gsa.gov/portal/getMediaData?mediaId=251343

[42] EnVerid. 2017. "Fully ASHRAE 62.1 Compliant." Accessed August 2017. Available at: http://www.enverid.com/hlr-module/ashrae

Energy Savings Potential

Potential Market and Replacement Applications

The technology affects ventilation fan consumption and space heating and cooling energy associated with outside air conditioning. The long-term potential market for reduced ventilation through advanced filtration is all commercial HVAC systems. Today, the products are currently sized for larger buildings with dedicated ventilation systems, so smaller buildings using RTUs for both space conditioning and ventilation may not currently be suitable venues. The technology can be installed in new or existing buildings, either within indoor mechanical rooms or on the building roof.

Energy Savings

Demonstrations with the DOE and GSA are underway, but past field studies suggest 20-35% HVAC energy savings for the advanced filtration technology:

- A 2015 field study at a University of Miami (FL) wellness center found a 28% reduction in total HVAC energy consumption by reducing outside airflow by 75%.[43]
- A 2016 field study at a large office building in Arkansas found a 36% decrease in peak HVAC loads by reducing outside airflow by 65%.[44]
- Other case studies show 22-35% energy savings.[45]

Cost and Complexity

Payback for the technology is dependent on the building design and location, with new installations in hot and humid climates, or cold climates with high utility costs, having quicker payback periods. EnVerid estimates a 3-year simple payback for target applications.[46] Where applicable, building designers could decrease peak cooling and/or heating load and downsize HVAC equipment, thereby reducing cost. The technology requires annual replacement of filter cartridges and sensor recalibration, but otherwise requires no additional maintenance or change in building operations.

Peak-Demand Reduction and Other Non-Energy Benefits

The advanced filtration technology offers substantial peak demand savings by decreasing the outside air requirement, and therefore HVAC energy load, during days that typically experience the most extreme electric power consumption. EnVerid estimates up to 40% reduction in peak demand for hot and humid climates.

The technology can ensure high IAQ by closely measuring and removing indoor contaminants directly, and testing has demonstrated significant reductions in formaldehyde and other VOCs.

Next Steps for Technology Development

Advanced filtration products that offer ventilation reduction opportunities are now available for commercial buildings in the U.S., but their use has been limited to date due to product awareness and market acceptance

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[43] EnVerid Systems Inc. 2017. "'Smart Scrubber' Manages HVAC Load, IAQ for Fitness & Wellness Center." HPAC Engineering. July 2017.Available at: http://www.hpac.com/iaq-ventilation/smart-scrubber-manages-hvac-load-iaq-fitness-wellness-center

[44] ACHR News. 2017. "ArcBest Corporate Headquarters Building." May 2017. Available at: http://www.achrnews.com/articles/134983-arcbest-corporate-headquarters-building

[45] EnVerid Website. Accessed August 2017. Available at: http://www.enverid.com/projects

[46] GSA. 2017. "Smart Scrubbers for HVAC Load Reduction." August 2017. Available at: https://www.gsa.gov/portal/getMediaData?mediaId=251343

issues. EnVerid is participating in several government and utility demonstrations to showcase the technology for different applications, which will support further adoption.

Table 17 lists potential next steps to advance ventilation reduction through advanced filtration.

Table 17: Recommended Next Steps for the Development of Ventilation Reduction through Advanced Filtration

Activities
Demonstrate the performance and energy savings of the technology in numerous climate zones and building types
Develop products suitable for light-commercial applications typically served by RTUs
Continue to work with building code agencies to expand the acceptance of the technology

4.4 Surface Coatings for Liquid Friction Reduction

Brief Description	Advanced surface coatings repel water and other contaminants from heat exchanger coils, reducing fouling and frost build up.

Technology Characteristics	Value	Comments
Technology Category	Technology Enhancements for Current Systems	
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)	Surface coating is an existing technology, however, several companies have next-generation products under development for different applications
Unit Energy Savings	10%	Conservative estimate based on expected energy savings from regular coil cleanings. Researchers predict 25-30% efficiency improvements (20% energy savings)
Technical Energy Savings Potential	114.2 TBtu	Vapor-compression cooling systems (except chillers) and heat pumps
Non-Energy Benefits	Potential for significant benefits, but not well documented	Potential for improved comfort for heat pump heating, reduced maintenance due to cleaner coils
Peak Demand Reduction Potential	Medium	For heat pumps, fewer defrost cycles could support winter peak demand reduction
Relative Cost Premium	Neutral	Unknown relative to conventional coatings, but vendors predict reasonable cost
Operational Complexity	Neutral	No changes in operational complexity other than during manufacturing

Background

Technology Description

The performance of refrigerant-to-air heat exchangers for RTUs, PTACs, and a variety of other types of HVAC equipment relies on the interaction of the heat exchanger surfaces with indoor or outdoor airstreams. When materials build up on heat exchangers, the efficiency and performance of the HVAC system decrease. For example, heat pumps require periodic defrost cycles to remove frost accumulation on the outdoor coil in winter, and both indoor and outdoor coils require regular cleanings to reduce fouling from dirt and dust.

Several research organizations and start-up companies (e.g., LiquiGlide, SLIPS Technologies, and Nelumbo) are developing advanced surface coatings that repel water and other materials better than current technologies. Figure 14 illustrates two concepts under development that use a specialized liquid overlayer to create a smooth, slippery surface that repels liquids. The SLIPS Technologies product (right image) binds the liquid directly with the material surface,[47] whereas the LiquiGlide product (left image) applies a textured surface, shown in green, on top of the material first, and then applies the liquid overlayer.[48] Nelumbo is developing a different

[47] SLIPS Technologies Website. Accessed August 2017. Available at: http://slipstechnologies.com/
[48] LiquiGlide Website. Accessed August 2017. Available at: https://liquiglide.com/

approach, using a ceramic technology that builds on the material through a multi-stage dip coat process.[49] Researchers expect these coatings to have greater ability to shed water through use of advanced materials. They expect the lifetime to be longer than current coatings due to binding and self-healing capabilities.

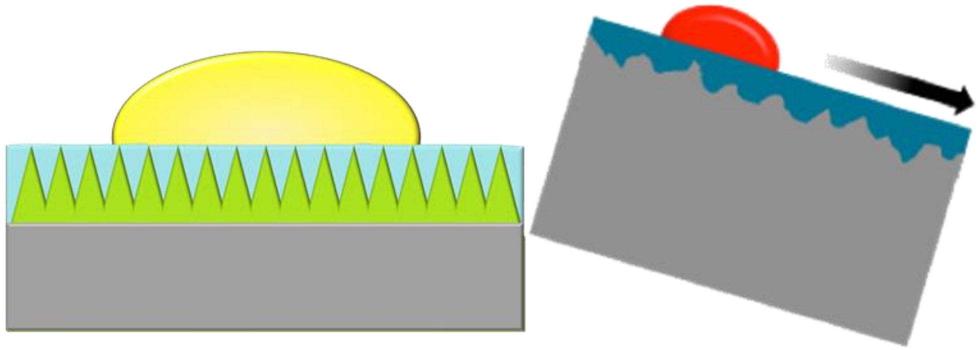

Figure 14: Example surface coating for liquid friction reduction concepts

Source: Left image from LiquiGlide (2017),[50] right image from SLIPS Technologies (2017)[51]

While unproven yet for commercial HVAC applications, equipment using this technology could achieve lower annual energy consumption by repelling water and other contaminants from outdoor and indoor coils. For example, heat exchangers could have lower fouling levels as the beaded water cleans away accumulating dirt and dust, and heat pumps could operate with fewer or shorter defrost cycles. The applications for these technologies extend beyond commercial HVAC systems, and developers are exploring the potential markets in industrial processes, product packaging, transportation, medical products, and other sectors.

Technical Maturity and Current Developmental Status

Specialized coating for HVAC heat exchangers is an established technology for corrosion resistance and other applications, and past research in this area found relatively minor improvements.[52] Limited information is available about the performance of the next-generation coatings for HVAC, refrigeration, and other air-side heat exchangers. The companies developing these coatings are start-ups that have spun off from university research, and are beginning their commercialization efforts. Nevertheless, SLIPS Technologies is in discussions with manufacturers and end-users in commercial refrigeration and cold storage markets, to conduct joint R&D and demonstration projects.[53]

Barriers to Market Adoption

In addition to proving energy savings and other operational benefits, the manufacturability, durability, and cost of the coatings need to be demonstrated to ensure success in HVAC heat exchanger applications. How the companies apply the coatings to materials will also impact their market adoption: some coatings can be

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[49] Berryman et al. 2016. "Nelumbo – Superhydrophobic Coatings for HVAC." University of California, Berkeley. Available at: https://ei.haas.berkeley.edu/education/c2m/docs/2016%20Finalists/Nelumbo%20App%20&%20Supp.pdf

[50] LiquiGlide Website. Accessed August 2017. Available at: https://liquiglide.com/tech/

[51] SLIPS Technologies Website. Accessed August 2017. Available at: http://slipstechnologies.com/about-slips/

[52] Moallem et al. 2013. "Effects of Surface Coating and Water Retention on Frost Formation in Microchannel Evaporators." HVAC&R Research May 2013. Available at: http://www.hvac.okstate.edu/sites/default/files/pubs/papers/2013/Moallem_et_al_2013.pdf

[53] Personal communication with Carl Fuda, Senior Associate with Anzu Partners, who is supporting SLIPS Technologies' commercialization efforts. August 8, 2017.

sprayed onto existing heat exchangers in the field, whereas others would be applied to new heat exchangers at the factory.

Energy Savings Potential

Potential Market and Replacement Applications

The new coating technologies would be technically applicable in all refrigerant-to-air heat exchangers for commercial HVAC applications, including most vapor-compression A/C systems and heat pump systems.

Energy Savings

Limited information exists about the performance of next-generation coatings for commercial HVAC heat exchangers. Nelumbo projects up to 25-30% energy efficiency increase,[54] but notes that laboratory and field testing are in progress.[55] Any benefit derived from water removal from the heat exchanger must balance any impact the coating has on heat transfer capabilities, fan energy consumption, or other performance characteristics. We conservatively estimate a 10% annual energy savings for advanced heat exchanger coatings in commercial HVAC applications based on the expected savings utility quality maintenance programs that include evaporator and condenser coil cleaning.[56]

Cost and Complexity

The product developers envision the products being applied during heat exchanger manufacturing, rather than in the field. The added cost of applying the surface coatings to HVAC heat exchangers during manufacturing is unknown. When applied during equipment production, the surface coating should create no adverse operational impacts, and it may improve equipment reliability by maintaining heat exchanger cleanliness.

Peak-Demand Reduction and Other Non-Energy Benefits

For space cooling, the summer peak demand reduction would be on the order expected from the energy savings benefit. For heat pumps, surface coatings that repel liquid could delay frost accumulation and decrease the frequency of defrost cycles, thus reducing winter peak demand.

Next Steps for Technology Development

Using the latest nanotechnology research, the next generation of surface coatings could have significant impacts across a number of industries in the coming years. Nevertheless, further research is needed to determine their energy savings and economic prospects in common refrigerant-to-air heat exchanger applications in building HVAC and refrigeration systems. Researchers should continue to develop products for this market and work with industry manufacturers regarding processes for applying the coatings during production.

Table 18 lists potential next steps to advance surface coatings for liquid friction reduction.

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[54] Nelumbo Website. Accessed August 2017. Available at: http://www.nelumbo.io/products/
[55] Berryman et al. 2016. "Nelumbo – Superhydrophobic Coatings for HVAC." University of California, Berkeley. Available at: https://ei.haas.berkeley.edu/education/c2m/docs/2016%20Finalists/Nelumbo%20App%20&%20Supp.pdf
[56] Illinois Statewide Technical Reference Manual for Energy Efficiency Version 6.0. Volume 2: Commercial and Industrial Measures. February 2017. Available at: http://ilsagfiles.org/SAG_files/Technical_Reference_Manual/Version_6/Final/IL-TRM_Effective_010118_v6.0_Vol_2_C_and_I_020817_Final.pdf

Table 18: Recommended Next Steps for the Development of Surface Coatings for Liquid Friction Reduction

Activities
Conduct laboratory testing with coatings applied to HVAC heat exchangers to understand the impacts on heat transfer, fan energy, fouling, frost buildup, and other performance characteristics.
Conduct field testing to understand the durability and performance of the coatings in various applications and environments
Discuss the laboratory and field test results with leading heat exchanger and equipment manufacturers to understand and meet key requirements for incorporating the coatings in their production processes

5 Alternative Electrically Driven Heat Pump Technologies

Alternative Electrically Driven Heat Pump Technologies use electricity as their primary energy input. They use advanced technologies (either vapor-compression or non-vapor-compression) to provide heating or cooling more efficiently. Table 19 provides a brief description and the final ranking of the selected high priority technology options within the Alternative Electrically Driven Heat Pump Technologies category.

Table 19: Brief Descriptions for Alternative Electrically Driven Heat Pump Technologies

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Membrane Cooling System (5.1)	Systems using specialized polymer membranes to transfer water across several assemblies that enable efficient dehumidification and evaporative cooling.	Technology Demonstration (TRL 5-6)	0.51	3.70
Metastable Critical-Flow Cycle (5.2)	A novel cooling cycle that uses a specialized converging-diverging nozzle to expand a high-pressure refrigerant, which decreases temperature as it evaporates supersonically.	Technology Development (TRL 3-4)	0.45	3.65
Thermoelastic Cooling System (5.3)	Systems that transfer heat by cyclically applying physical stress to a specialized elastocaloric (shape memory alloy, or SMA) material that changes temperature when compressed and released.	Technology Development (TRL 3-4)	0.41	3.35
S-RAM Heat Pump (5.4)	A system that uses double-ended pistons to couple the compression and expansion processes of a vapor-compression cycle, achieving higher efficiencies.	Technology Development (TRL 3-4)	0.25	3.30
Turbo-Compressor-Condenser-Expander Heat Pump (5.5)	A system that combines multiple vapor compression components into a joint assembly operating on a common shaft for improved work recovery and energy efficiency.	Technology Development (TRL 3-4)	0.31	2.85
Electrocaloric Cooling System (5.6)	Specialized electrocaloric materials are oscillated in an electric field, which causes them to experience reversible temperature change and transfer heat.	Early Stage Research (TRL 1-2)	0.26	2.85

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Electrochemical Heat Pump (5.7)	An electrochemical cell using a proton exchange membrane compresses a hydrogen working fluid to drive a vapor-compression or metal-hydride heat pump cycle.	Technology Development (TRL 3-4)	0.21	2.85
Magnetocaloric Cooling System (5.8)	A system in which specialized magnetocaloric materials are cyclically exposed to a changing magnetic field, creating a reversible temperature change in the material that drives the cooling cycle.	Technology Development (TRL 3-4)	0.21	2.50

5.1 Membrane Cooling System

Brief Description	Systems using specialized polymer membranes to transfer water across several assemblies that enable efficient dehumidification and evaporative cooling.

Technology Characteristics	Value	Comments
Technology Category	Alternative Electrically Driven Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)	Laboratory prototype (7.5-ton capacity) under development at ORNL
Unit Energy Savings	50%	Performance estimates for membrane cooling system designs range from 35% to 89% savings
Technical Energy Savings Potential	496.5 TBtu	Includes all vapor-compression type air cooling systems except chillers
Non-Energy Benefits	1-2 quantified benefits	Zero-GWP working fluids reduce direct greenhouse gas (GHG) emissions, potential for improved comfort through separate sensible and latent cooling
Peak Demand Reduction Potential	Low	Peak demand reduction is comparable with energy savings
Relative Cost Premium	Moderately higher upfront cost	Expected to have moderately higher cost at scale, but prototype uses specialized components
Operational Complexity	Moderately higher complexity	Systems require multiple air, vapor, and liquid circuits and specialized components with unknown reliability. Potentially greater water consumption

Background

Technology Description

Traditional packaged A/C systems use a single cooling stage to reduce both sensible heat (i.e., temperature) and latent heat (i.e., humidity) of the supply air stream. In humid regions, the A/C system must “overcool” the air to remove humidity, which then requires a downstream heating element to deliver the supply air at comfortable temperatures. Researchers have developed membrane dehumidification systems that decouple humidity control from temperature control and enable more efficient space conditioning, especially for humid regions. These systems use specialized polymer membranes that can passively and efficiently remove water from an airstream, without relatively little change in air temperature. A separate sensible cooling stage (e.g., vapor-compression cycle, evaporative cooler, etc.) then reduces the airstream’s temperature before it enters the conditioned space.

Figure 15 highlights the cooling portion of an A/C system under development that uses the membrane material for both latent and sensible cooling stages. The system operates by creating pressure differentials across the membrane assemblies, using a series of vapor compressors and pumps:

- After some pre-conditioning, outside air enters a membrane dehumidifier in which a vapor compressor is creating a partial vacuum to pull the input air’s moisture across the membrane.

- The system's sensible cooling stage contains an evaporative chiller with a membrane in contact with liquid water. Under a partial vacuum, the liquid water evaporates as it is drawn through the membrane, cooling the remaining liquid water. The air is cooled as it flows across a heat exchanger in contact with the cold liquid water.
- The current prototype uses an electrochemical vapor compression system (Section 5.7) to drive the membrane chiller, as well as a membrane humidifier (not shown) to exhaust heat and moisture from the system.

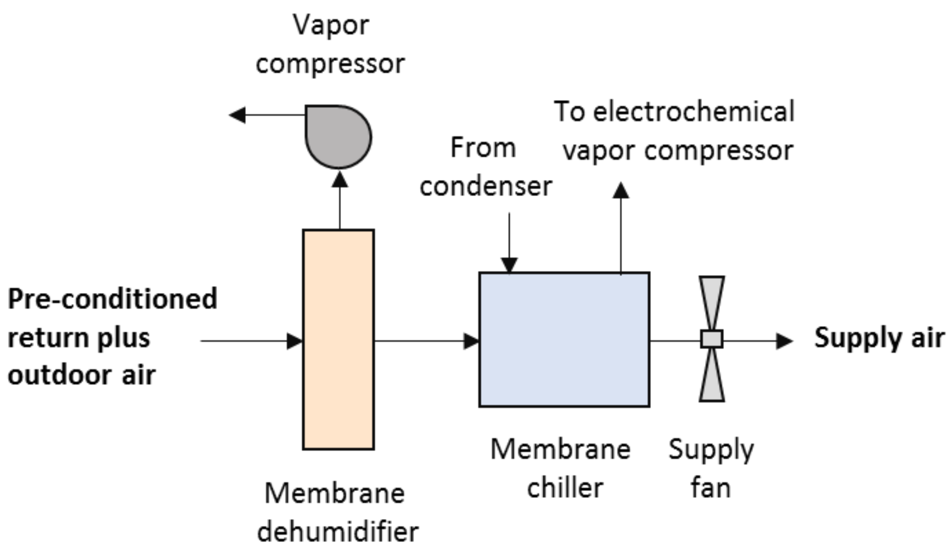

Figure 15: Schematic of membrane cooling system

Source: Simplified diagram based on Johnson (2017)[57]

Technical Maturity and Current Developmental Status

Supported by funding from U.S. DOE BTO, Dais Analytic[58] is working with ORNL and industry partners to adapt their membrane technology, which is commercialized for energy recovery ventilators (ERVs) and other products. The current research project will develop a 7.5 ton packaged rooftop unit (RTU) replacement for laboratory testing, building on prior research funded by ARPA-e and other organizations.[59]

Other organizations are also investigating the potential of membrane-based dehumidification and A/C systems. For example, researchers at TAMU are exploring a concept that combines membrane dehumidification with an evaporative cooling system. The group has created a start-up, Claridge-Culp, to further develop the technology, and they plan to test a prototype in 2018.[60]

[57] Johnson, Brian. 2017. "Membrane Based Air Conditioning." Dais Analytic Corporation. Presented at 2017 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2017/04/f34/4_312108_Johnson_031517-1200.pdf

[58] Dais Analytic Corporation. 2017. "Nanoair." Accessed August 2017. Available at: https://daisanalytic.com/applications/nanoair/

[59] Johnson, Brian. 2017. "Membrane Based Air Conditioning." Dais Analytic Corporation. Presented at 2017 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2017/04/f34/4_312108_Johnson_031517-1200.pdf

[60] Bloom, Aubrey. 2016. "Claridge-Culp Aims to Change the World with Air Conditioning." Texas A&M Engineering Experiment Station. October 10, 2016. Available at: http://tees.tamu.edu/news/2016/10/10/claridge-culp-aims-to-change-the-world-with-air-conditioning/?_ga=2.104066694.766156906.1502115742-479676887.1502115742

Barriers to Market Adoption

Further technology development is necessary to evaluate the market adoption potential for membrane A/C systems. Conventional A/C systems are highly reliable, and current membrane A/C research have encountered challenges with vapor compressors, membrane assemblies, and other components.[61] The system uses water as the primary working fluid. Water consumption for building cooling is a concern in some U.S. regions, however the exact input/output balance of water for membrane A/C is as yet unknown.

Energy Savings Potential

Potential Market and Replacement Applications

Hot, humid regions would experience the greatest potential energy savings from separate sensible and latent cooling systems, but membrane heat pumps are feasible for most packaged A/C applications. Technically, the systems could potentially serve buildings with chilled water plants, but current prototypes focus on air-side applications.

Energy Savings

Researchers from Dais Analytic project 54-89% energy savings for the membrane A/C system under development, compared to conventional systems.[62] These projections align with previous estimates for the technology with SEER greater than 30.[63] The research team at TAMU and Claridge-Culp project that their membrane A/C concept could offer 35-50% energy savings, once developed.[64]

Cost and Complexity

Membrane cooling systems could have similar cost and complexity to conventional A/C systems, but additional prototype development is necessary to quantify manufacturability, cost, and operational attributes. The membrane materials and vapor compressor components are already commercialized for other applications, but the dehumidifier, humidifier, and chiller assemblies require different configurations and fabrication techniques. In addition, Dais Analytic system plans to incorporate an electrochemical compressor, which is also at an early stage of development for A/C systems (Section 5.7).[65]

Peak-Demand Reduction and Other Non-Energy Benefits

Peak demand reduction should be comparable with energy savings. The technology could provide improved comfort and IAQ by controlling temperature and humidity separately. In addition, membrane A/C systems use water as the primary working fluid, rather than refrigerants with GWP impacts.

Next Steps for Technology Development

Membrane cooling systems are a promising technology for improving the comfort and efficiency of commercial buildings through separate sensible and latent control and natural working fluids. The major

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[61] Johnson, Brian. 2017. "Membrane Based Air Conditioning." Dais Analytic Corporation. Presented at 2017 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2017/04/f34/4_312108_Johnson_031517-1200.pdf

[62] Ibid

[63] Dais Analytic Corporation. 2013. "Using the Aqualyte™ family of disruptive nanomaterials to provide unparalleled functionality in sustainable applications." Presented at 2013 ARPA-e Innovation Summit. 2013. Available at: http://www.arpae-summit.com/paperclip/exhibitor_docs/13AE/Dais_Analytic_Corporation_90.pdf

[64] Claridge et al. 2016. "Compressor Needs for the Claridge-Culp-Pate Refrigeration Cycle Based on Membrane Enabled Air Dehumidification and Cooling." 2016 Purdue Compressor Conference. Available at: https://www.researchgate.net/publication/309564371_Compressor_Needs_for_the_Claridge-Culp-Pate_Refrigeration_Cycle_Based_on_Membrane_Enabled_Air_Dehumidification_and_Cooling

[65] Johnson, Brian. 2017. "Membrane Based Air Conditioning." Dais Analytic Corporation. Presented at 2017 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2017/04/f34/4_312108_Johnson_031517-1200.pdf

challenges lie with developing the advanced membrane assemblies and integrating them into a complete A/C system. Because of the wide range of applications for the technology, research on market attractiveness is also needed to determine the best initial target markets (e.g., dedicated outside air systems [DOAS], RTU with gas heating, dehumidification-only, etc.) and to further inform product development.

Table 20 lists potential next steps to advance membrane cooling systems.

Table 20: Recommended Next Steps for the Development of Membrane Cooling Systems

Activities
Continue development of membrane-based dehumidification and chiller components
Conduct laboratory testing with current prototypes to quantify dehumidification and space cooling capacity, efficiency, and other performance capabilities
Develop a near-production prototype for long-term laboratory or field testing to determine cost, reliability, and other operational attributes

5.2 Metastable Critical-Flow Cycle

Brief Description	A novel cooling cycle that uses a specialized converging-diverging nozzle to expand a high-pressure refrigerant, which decreases temperature as it evaporates supersonically.

Technology Characteristics	Value	Comments
Technology Category	Alternative Electrically Driven Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	Laboratory testing and modelling to understand the underlying physics of the nozzle flow region, and preparing for next stage of laboratory testing
Unit Energy Savings	30%	Estimated 30% savings for chillers. Researchers believe that cooling cycle coefficient of performance (COP) could approach 10 and greater, but prototype development is several years away.
Technical Energy Savings Potential	473.1 TBtu	Potential to replace most vapor-compression cooling systems
Non-Energy Benefits	1-2 quantified benefits	Ability to use zero- or low-GWP working fluids and reduce direct GHG emissions; lower noise than compressors
Peak Demand Reduction Potential	Low	Peak demand reduction as expected from average level of energy savings
Relative Cost Premium	Neutral	Cost for systems is unknown, but the nozzle assembly is expected to use available manufacturing processes, and the remainder of the cycle is commercially available
Operational Complexity	Neutral	Operational characteristics are unknown. The number of moving parts could potentially be lower, but size may be an issue due to the system design and mass flow rates.

Background

Technology Description

Conventional vapor-compression cycles use an expansion device to decrease the pressure of the condensed liquid refrigerant before it enters the evaporator. Decreasing refrigerant pressure causes a portion of the fluid to evaporate, which decreases its temperature before it enters the evaporator. Researchers at Kansas State University (KSU) have investigated a refrigeration cycle that effectively combines the expansion valve, evaporator, and condenser into a single device. The KSU technology uses a converging-diverging nozzle to expand a high-pressure refrigerant, once it reaches supersonic or critical-flow conditions. The nozzle itself acts as a heat exchanger to absorb heat from a secondary working fluid (e.g., water) that can then provide space cooling for buildings.

Figure 16 presents results from laboratory testing of the metastable critical-flow cycle (MCFC), showing temperatures at several places in the nozzle assembly with and without an external heat source (“0W” and “607W,” respectively). A high-pressure pump sends liquid refrigerant into a specially designed nozzle-plus-heat-exchanger assembly (Figure 17). Fluid flow through the nozzle is extremely complex, dependent on the fluid involved, and not yet entirely understood. It is known, though, that some or all of the fluid reaches or exceeds sonic velocity, and a portion of the liquid evaporates with accompanying absorption of heat and drop in fluid temperature (the evaporator portion of the nozzle). The KSU nozzle design reverts the fluid back to subsonic conditions, condensing refrigerant vapor back to a liquid (the condenser portion).[66]

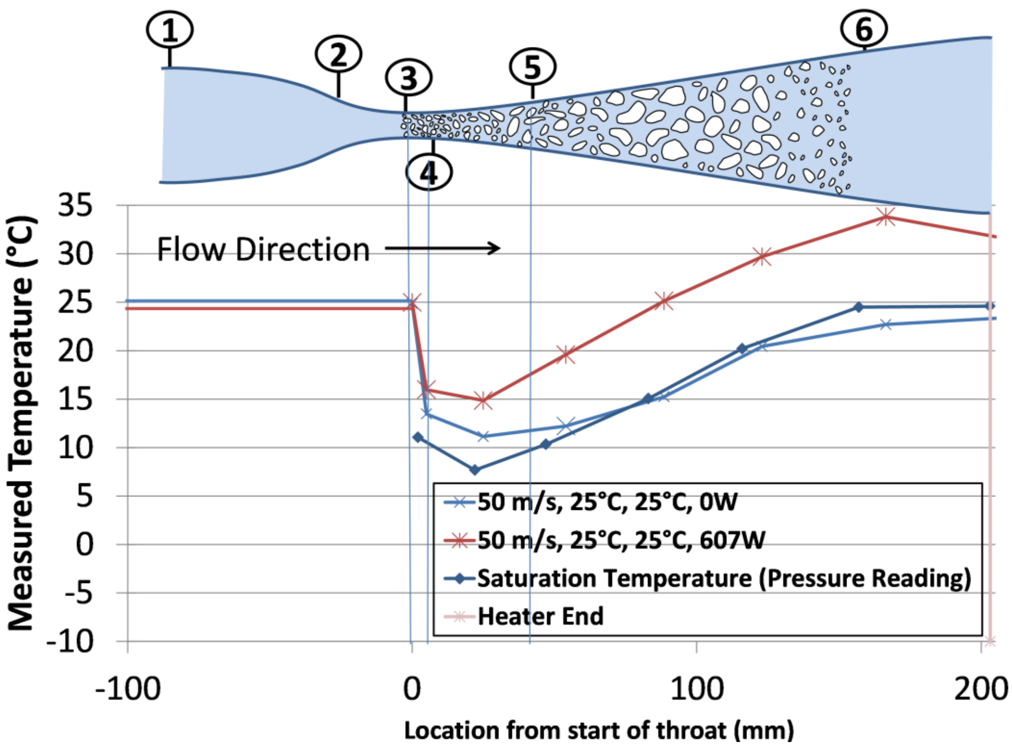

Figure 16: Measured temperatures in an experimental MCFC nozzle

Source: KSU (2017)[67]

Figure 17 is a diagram of the critical-flow refrigeration cycle. The system replaces a vapor compressor with a high-pressure liquid pump and, as mentioned, uses the nozzle assembly as both the evaporator and condenser. The system can potentially achieve higher efficiencies than conventional systems through this combined approach and its low pumping requirements, but the cycle does require higher mass flow rates.[68]

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[66] Hosni, Mohammad. 2014. "Development of a Water Based, Critical Flow, Non-Vapor Compression Cooling Cycle." Kansas State University. March 2014. Available at: https://www.osti.gov/scitech/servlets/purl/1129868
[67] Personal communication with KSU researchers. August 15, 2017
[68] Gielda, Thomas. 2011. "Impact of High-Performance Computing on New Product Design: A Case Study for a Novel Cooling System." July 2011. Available at: http://www.mcs.anl.gov/uploads/cels/papers/scidac11/final/GIELDA_SCIDDAC_JULY%20(final).pdf

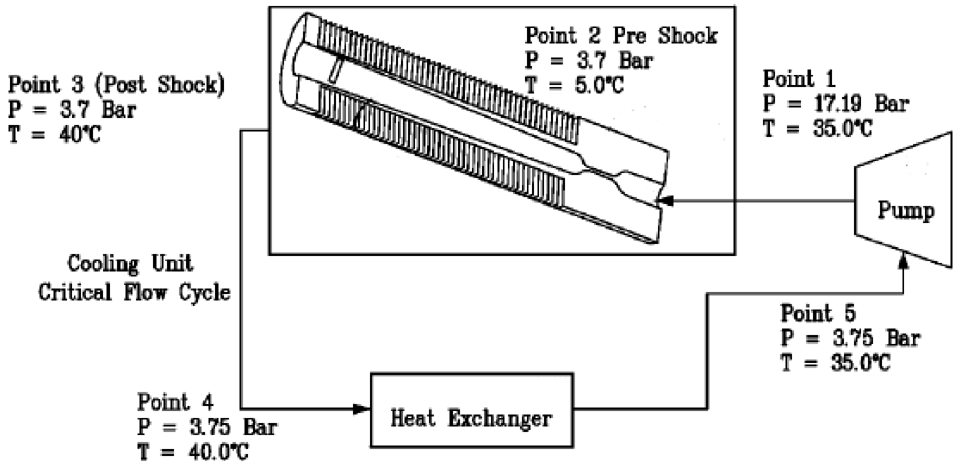

Figure 17: Schematic of an MCFC system

Source: Debus et al. (2012)[69]

Technical Maturity and Current Developmental Status

With funding from DOE and venture-capital investors, PAX Streamline and later Caitin conducted initial research in the late 2000s,[70] with researchers at KSU continuing development through 2014.[71] The KSU team has continued analysis and testing with internal funding and has applied for a new patent on improvements to the critical-flow refrigeration cycle.[72] Overall, the technology is still in the early stages of development, but researchers have successfully demonstrated the cooling capabilities of the cycle (18 °C).[73]

Barriers to Market Adoption

The technology is in early laboratory experimentation with uncertain final performance, cost, size, and other attributes that will affect its market adoption potential. Because the cooling region within the nozzle has a short length, transferring heat from the secondary fluid circuit has proved challenging. The high mass flow rate and cycle design may require an array of nozzles in order to reach required cooling capacities, which could cause size issues.

Energy Savings Potential

Potential Market and Replacement Applications

The technology is potentially applicable for a wide range of space cooling applications. Large commercial chillers represent one of the clearest applications of the technology, due to the requirement of a secondary working fluid to transfer heat with the nozzle assembly.

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[69] Debus et al. 2012. "Supersonic Cooling Nozzle Inlet." WIPO Patent No.: WO 2012/018627 A1. February 9, 2012.
[70] Gielda, Thomas. 2011. "Impact of High-Performance Computing on New Product Design: A Case Study for a Novel Cooling System." July 2011. Available at: http://www.mcs.anl.gov/uploads/cels/papers/scidac11/final/GIELDA_SCIDDAC_JULY%20(final).pdf
[71] Hosni, Mohammad. 2014. "Development of a Water Based, Critical Flow, Non-Vapor Compression Cooling Cycle." Kansas State University. March 2014. Available at: https://www.osti.gov/scitech/servlets/purl/1129868
[72] Personal communication with KSU researchers. August 15, 2017
[73] Hosni, Mohammad. 2014. "Development of a Water Based, Critical Flow, Non-Vapor Compression Cooling Cycle." Kansas State University. March 2014. Available at: https://www.osti.gov/scitech/servlets/purl/1129868

Energy Savings

Researchers project that the critical-flow refrigeration cycle could provide system COPs of up to 10, or even greater, but further R&D is necessary to develop breadboard prototypes of a system. Analysis of the results of current laboratory testing showed an estimated COP of 1.7 for the 18 °C temperature drop. Researchers believe the next phases of laboratory experimentation will demonstrate a COP of 4.1, when including new designs, and with optimized nozzle geometry can reach a COP in the range of 8 to 15. We conservatively project that this technology could provide an estimated 30% savings for commercial buildings, when including the parasitic energy consumption of the secondary heat transfer loop (i.e., nozzle to building), radiator, and other processes.

Cost and Complexity

The cost and complexity of the technology are largely unknown at this stage. Most components are commercially available, and the nozzle assembly is expected to use available manufacturing processes. Beside the nozzle, the circuit design and other components could be simpler and lower cost than conventional systems because the refrigerant fluid remains in liquid phase throughout the circuit. Like conventional chillers, the system requires a secondary working fluid to deliver space cooling to buildings.

Peak-Demand Reduction and Other Non-Energy Benefits

Peak-demand reduction would be as expected from the average level of energy savings. The nozzle can be tailored to any number of zero- or low-GWP working fluids. Liquid pumps have lower noise than vapor compressors, which could decrease sound and vibration relative to current systems

Next Steps for Technology Development

Recent MCFC developments demonstrate the technology's promising potential for commercial HVAC applications, but challenges remain to determining the performance, efficiency, and operational attributes of a complete system. Further research is necessary to optimize nozzle designs and construct a full prototype for testing to determine total system performance.

Table 21 lists potential next steps to advance the metastable critical-flow cycle technology.

Table 21: Recommended Next Steps for the Development of the Metastable Critical-Flow Cycle

Activities
Continue to conduct laboratory research on the fundamental physics of the cycle to understand the multi-phase heat transfer in nozzle.
Develop optimized nozzle geometries and designs to demonstrate improved performance, efficiency, and transfer of heat with the secondary fluid system.
Construct bench prototypes to demonstrate the cooling cycle, its operating parameters, and its performance.

5.3 Thermoelastic Cooling System

Brief Description	Systems that transfer heat by cyclically applying physical stress to a specialized elastocaloric (shape memory alloy, or SMA) material that changes temperature when compressed and released.

Technology Characteristics	Value	Comments
Technology Category	Alternative Electrically Driven Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	Several laboratory prototypes under development
Unit Energy Savings	40% cooling	Projected space cooling savings over conventional packaged commercial A/C systems
Technical Energy Savings Potential	397.2 TBtu	All vapor-compression type air cooling systems except chillers
Non-Energy Benefits	1-2 quantified benefits	Non-vapor-compression technology that avoids the usage of refrigerants with GWP, reducing direct GHG emissions; lower noise without compressor
Peak Demand Reduction Potential	Low	Peak demand reduction would be as expected from average level of energy savings, unless thermal storage was integrated into the system design (e.g., water bath)
Relative Cost Premium	Moderately higher upfront cost	Under mass production, cost is expected to be roughly on par with that of vapor-compression systems
Operational Complexity	Moderately higher complexity	SMA materials and processes are straightforward, but the number of stages and maintenance of the system could prove complicated

Background

Technology Description

Thermoelastic or elastocaloric heat pumps use the unique properties of shape memory alloy (SMA) materials to cyclically transfer heat at suitable temperature differences. Figure 18 exhibits the elastocaloric effect, showing how SMAs change temperature when stress is applied and released. When high physical pressure or tension is applied, SMAs undergo an austenite to martensite phase change, raising the temperature of the material due to latent heat release. When the stress is released, the SMA reverses its phase change and absorbs heat from its environment. By cyclically loading and unloading the SMA, heat can be transferred to and from the materials as a heat pump cycle.

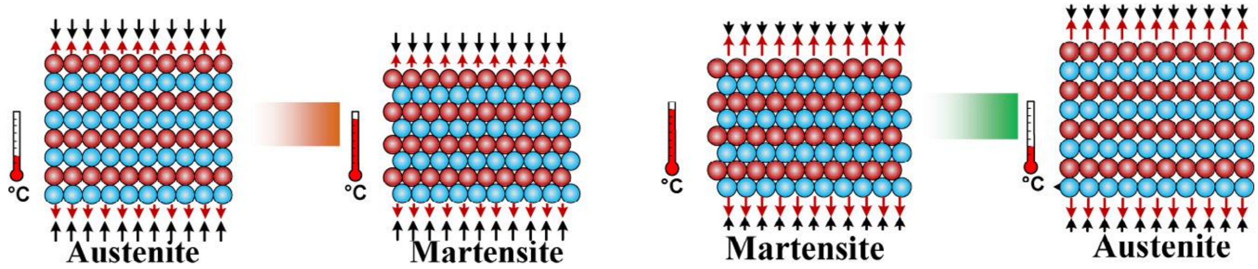

Figure 18: Illustration of elastocaloric effect when stress is applied and released

Source: Qian et al. (2015)[74]

Many researchers have demonstrated the thermoelastic cooling concept with different SMAs, but developing an integrated system for building space conditioning has been challenging. Qian et al. (2015) summarizes several different thermoelastic cooling system designs.[75] In small-scale laboratory testing, thermoelastic materials have exhibited up to 20°C temperature differences[76] and COPs greater than ten,[77] but these tests only showed the potential for the materials rather than the performance of a usable HVAC system. Researchers have developed several concepts to create a more continuous process and effectively transfer heat from an SMA to a secondary working fluid.[78] A recent prototype under development features a looped SMA belt that travels between two rollers that apply the compressive force to create the thermoelastic effect, shown in Figure 19. Once leaving the rollers, the SMA undergoes phase transitions back to austenite, absorbing heat from the water it passes through and decreasing the water temperature. Since this process is continuous, the chilled water could service a building's HVAC system.

[74] Qian et al. 2015. "A Review of Elastocaloric Cooling: Materials, Cycles and System Integrations." International Journal of Refrigeration. Volume 26, 2016. Published online December 21, 2015. Available at: http://www.mse.umd.edu/sites/default/files/190.pdf

[75] Ibid

[76] Ibid

[77] Maryland Energy Sensor and Technologies. 2017. "Our Technology." Accessed August 2017. Available at: http://www.energysensortech.com/ourtech.html

[78] Takeuchi, Ichiro. 2017. "Compact Thermoelastic Cooling System." Maryland Energy and Sensor Technologies, LCC. 2017 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2017/04/f34/13_312109_Takeuchi_31417-1630.pdf

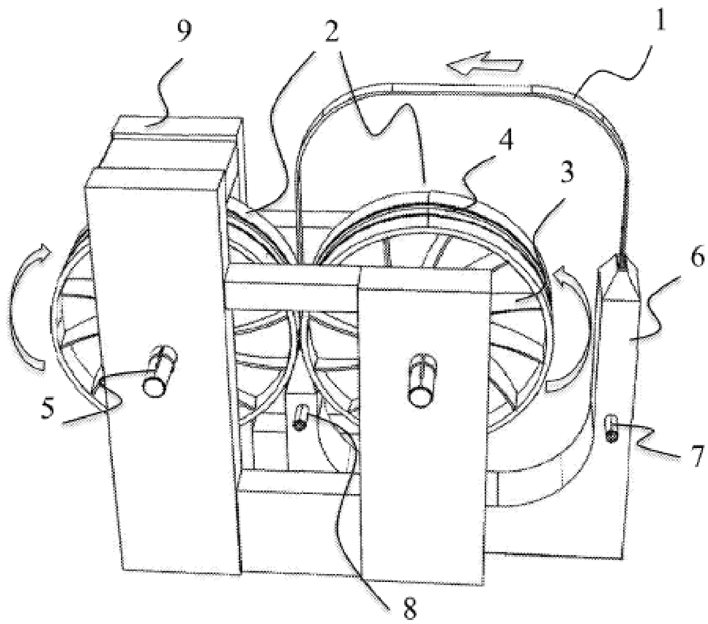

Figure 19: Illustration of prototype thermoelastic cooling system

Source: Cui and Takeuchi (2017)[79]

Technical Maturity and Current Developmental Status

Under support from DOE BTO and ARPA-e, researchers at the UMD and the start-up company Maryland Energy and Sensor Technologies are continuing to develop thermoelastic cooling prototypes for use in building A/C systems. The current prototype has demonstrated 40 W cooling capacity to date, with a goal of 400 W continuous cooling with a COP greater than four.[80]

Barriers to Market Adoption

Thermoelastic cooling systems are still in early stages of development. Researchers need to overcome barriers related to material limitations (e.g., low specific heat capacity, thermal conductivity, temperature lift, and lifetime), system limitations (e.g., the need to have a secondary heat transfer fluid), and cost-effectiveness relative to conventional HVAC systems. [81]

Energy Savings Potential

Potential Market and Replacement Applications

In the long term, thermoelastic heat pumps could technically replace most vapor-compression type HVAC systems, but their development for different applications will depend on the technologies advantages in specific markets. Current developments focus on packaged space cooling applications (e.g., RTUs, packaged terminal A/Cs (PTAC)) rather than chillers or heat pump space heating.

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[79] Cui and Takeuchi. 2017. "Compact Thermoelastic Cooling System." U.S. Patent No. US20170138648 A1. Available at: https://www.google.com/patents/US20170138648

[80] Takeuchi, Ichiro. 2017. "Compact Thermoelastic Cooling System." Maryland Energy and Sensor Technologies, LCC. 2017 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2017/04/f34/13_312109_Takeuchi_31417-1630.pdf

[81] Cui et al. 2015. "Advancing Caloric Materials for Efficient Cooling: Key Scientific and Device-Related Materials Challenges for Impact." University of Maryland. December 2015. Available at: https://www.nanocenter.umd.edu/events/amec/2015.Workshop.Advancing_Caloric_Materials.REPORT.pdf

Energy Savings

Researchers currently project thermoelastic cooling systems could provide 40% energy savings for commercial buildings, once fully developed.[82] Current prototype development will provide insight into the performance of a system that uses a secondary working fluid, which will inform the next stage of integrated prototypes.

Cost and Complexity

Under mass production, cost is expected to be similar to vapor-compression systems, but it is not yet known. SMA materials and processes are straightforward, but the number of stages and maintenance of the system could prove complicated. This will depend on how the SMA materials, secondary working fluids, and other systems interact in an integrated product.

Peak-Demand Reduction and Other Non-Energy Benefits

The magnitude of peak demand savings would be as expected from average level of energy savings. Savings could be larger if the water bath could serve as a thermal storage system by charging during off-peak times.

Other benefits include the use of SMA materials, rather than high-GWP refrigerants, to provide the cooling effect, as well as lower noise without use of compressor.

Next Steps for Technology Development

Thermoelastic cooling systems have progressively advanced in both cooling capacity, temperature lift, and efficiency in recent years, but significant R&D is necessary to develop an SMA-based packaged A/C system that would be ready for field testing and commercialization.

Table 22 presents potential next steps for advancing thermoelastic cooling systems.

Table 22: Recommended Next Steps for the Development of Thermoelastic Cooling Systems

Activities
Continue to develop laboratory prototypes to understand the performance and efficiency of current materials and system designs
Continue to investigate and develop different thermoelastic materials that meet necessary heat transfer and material properties
Develop next-generation prototypes that can more closely mimic the form factor and operating parameters of conventional A/C systems

[82] Takeuchi, Ichiro. 2017. "Compact Thermoelastic Cooling System." Maryland Energy and Sensor Technologies, LCC. 2017 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2017/04/f34/13_312109_Takeuchi_31417-1630.pdf

5.4 S-RAM Heat Pump

Brief Description	A system that uses double-ended pistons to couple the compression and expansion processes of a vapor-compression cycle, achieving higher efficiencies.

Technology Characteristics	Value	Comments
Technology Category	Alternative Electrically Driven Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	Initial prototype development
Unit Energy Savings	30%	Compared to packaged RTU performance
Technical Energy Savings Potential	241.2 TBtu	HVAC energy consumption for RTUs
Non-Energy Benefits	1-2 quantified benefits	Uses R-729 or air, the latter of which has zero GWP and reduced direct GHG emissions
Peak Demand Reduction Potential	Low	Peak demand reduction would be as expected from average level of energy savings
Relative Cost Premium	Neutral	Unknown incremental cost once ready for commercialization; uses advanced manufacturing techniques but may have material savings
Operational Complexity	Moderately lower complexity	Systems operate without oil

Background

Technology Description

S-RAM Dynamics has developed a unique mechanical assembly that converts rotary shaft motion into reciprocating piston motion (or vice versa) for use as an engine, compressor, pump, or expander in a variety of applications.[83] For HVAC and refrigeration (HVAC&R) systems, the Sanderson Rocker Arm Mechanism (S-RAM) would use double-ended pistons to couple both the compression and expansion devices and achieve higher efficiencies. As shown in Figure 20, the S-RAM device uses one or more double-ended pistons, where an electric motor creates reciprocating motion for both the compressor piston and expander piston. Through this coupled configuration, a portion of the expansion work is translated to the compression piston, reducing the required energy consumption of the system. In addition, the S-RAM assembly can continually adjust the expansion and compression speeds to match the required temperature and capacity requirements for additional energy savings.

[83] S-RAM Dynamics. Accessed August 2017. Available at: http://www.s-ram.com/how-it-works

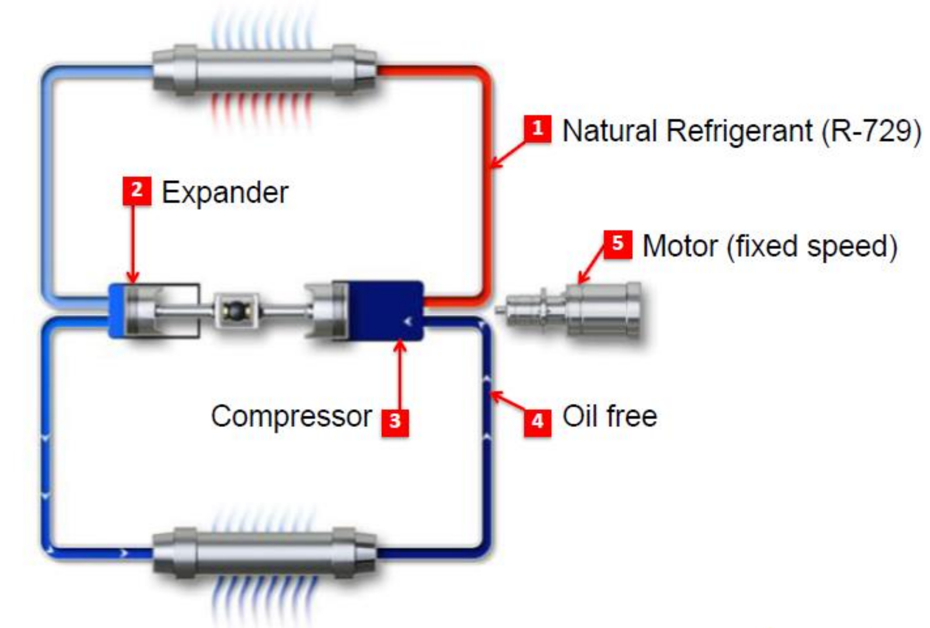

Figure 20: Schematic of S-RAM heat pump concept

Source: Jestings (2016)[84]

Technical Maturity and Current Developmental Status

Under support of the U.S. DOE BTO, S-RAM is developing the technology with ReGen Power, Purdue University, and ORNL for use in a 10-ton commercial heat pump RTU using air (R-729) as the refrigerant. The core S-RAM compressor is currently being tested at Purdue laboratories,[85] with heat exchangers and prototype development to be performed with ORNL.[86] The U.S. Army is also funding development of an S-RAM mobile refrigeration system using CO_2 as a refrigerant.[87]

Barriers to Market Adoption

The S-RAM technology does not appear to have undergone any benchtop or full prototype testing as a heat pump, and the projected performance is based on modeling. The likely performance, efficiency, reliability, manufacturability, cost, and other attributes are unknown at this time. If successfully developed at reasonable cost, the S-RAM heat pump could operate like conventional RTUs and have few barriers.

Energy Savings Potential

Potential Market and Replacement Applications

The target market for the technology is packaged RTUs for commercial buildings, both A/C-only and heat pumps.

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[84] Jestings, Lee. 2016. "Natural Refrigerant (R-729) Heat Pump." 2016 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2016/04/f30/31291_Jestings_040616-1635.pdf
[85] Ibid
[86] Dehoff, Ryan. 2016. "The New S-RAM Air Variable Compressor/Expander for Heat Pump and Waste Heat to Power Application." ORNL. May 23, 2016. Available at: http://info.ornl.gov/sites/publications/files/Pub67789.pdf
[87] S-RAM Dynamics. 2016. "S-RAM Dynamics to Produce State of the Art Refrigeration System Using New CO_2 Energy Recovery Compressor." March 2016. Available at: http://www.s-ram.com/news-and-press-release/6-u-s-army-awards-research-contract-for-next-generation-co2-refrigeration-system

Energy Savings

The technology developers predict that the S-RAM heat pump could provide 30-50% energy savings for commercial RTUs through the coupled compressor/expander and variable capacity capabilities.[88] They are particularly optimistic about its use in heat pumps for cold climates. As noted previously, these estimates are based on early modelling, rather than physical prototype testing.

Cost and Complexity

At this early stage, the cost and complexity of this technology is largely unknown, but the technology developers predict payback of less than four years.[89] Once fully developed with some modifications, the system could operate similar to conventional RTUs. Using air as a refrigerant may require larger heat exchangers and other specific requirements, but the product would also eliminate HFC refrigerant and compressor variable frequency drive (VFD) costs.

Peak-Demand Reduction and Other Non-Energy Benefits

The technology is not expected to have a large peak-demand benefit, beyond what would be expected from the average level of energy savings. Air is a natural refrigerant with zero GWP.

Next Steps for Technology Development

The S-RAM assembly is a promising technology for a variety of HVAC&R and power-related applications, but it requires additional R&D before its prospects relative to conventional technologies can be evaluated. Once fully developed, a high-efficiency heat pump with a coupled expander/compressor, using air as a refrigerant, would be attractive for commercial buildings.

Table 23 presents the potential next steps to advance S-RAM heat pump.

Table 23: Recommended Next Steps for the Development of S-RAM Heat Pump

Activities
Continue laboratory testing to understand the performance of the S-RAM assembly as both a compressor and expander for HVAC&R systems
Develop a laboratory prototype of a heat pump using the S-RAM assembly as a coupled compressor/expander with air or other working fluids
Develop a fully integrated prototype for laboratory and field testing to evaluate performance in various realistic conditions

[88] Dehoff, Ryan. 2016. "The New S-RAM Air Variable Compressor/Expander for Heat Pump and Waste Heat to Power Application." ORNL. May 23, 2016. Available at: http://info.ornl.gov/sites/publications/files/Pub67789.pdf
[89] Jestings, Lee. 2016. "Natural Refrigerant (R-729) Heat Pump." 2016 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2016/04/f30/31291_Jestings_040616-1635.pdf

5.5 Turbo-Compressor-Condenser-Expander Heat Pump

Brief Description	A system that combines multiple vapor compression components into a joint assembly operating on a common shaft for improved work recovery and energy efficiency.

Technology Characteristics	Value	Comments
Technology Category	Alternative Electrically Driven Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	Prototypes under development for laboratory testing
Unit Energy Savings	30%	Estimated 20 SEER performance for residential-type split-system configuration (14 SEER baseline)
Technical Energy Savings Potential	297.9 TBtu	All vapor-compression type air cooling systems except chillers
Non-Energy Benefits	Potential for significant benefits, but not well documented	Opportunity to use CO_2 as a refrigerant and achieve performance and efficiency comparable to current refrigerants with reduced direct GHG emissions
Peak Demand Reduction Potential	Low	Peak demand reduction would be as expected from average level of energy savings
Relative Cost Premium	Neutral, unknown	Potentially comparable cost, but currently unknown
Operational Complexity	Medium	High revolutions per minute (RPM) creates potential safety issues, but also reduces number of components

Background

Technology Description

Conventional A/Cs and heat pumps perform each stage of the vapor-compression cycle (compression, condensation, expansion, and evaporation) using separate assemblies. While manufacturers have achieved good reliability and increasingly higher efficiencies, this process requires multiple motors to circulate refrigerant and transfer heat to and from the various assemblies. Researchers at Appollo Wind Technologies[90] have developed an alternative heat pump design that uses a combined assembly operating on a common shaft for improved work recovery and energy efficiency.

The exact configuration can vary, but the core technology involves a series of hollow spokes connected to a central hub that is driven by an electric motor.[91]

- Refrigerant enters the hub/spoke assembly and the centrifugal force of the rotation compresses the refrigerant as it travels outward.

[90] Appollo Wind Technologies. Accessed August 2017. Available at: http://www.appollowind.com/Default.aspx
[91] Swett and Drane. 2016. "Turbo-compressor-condenser-expander." US Patent Application US20160138612A1. May 2016.

- The spokes are shaped as airfoils to pull air across the assembly and condense the refrigerant.
- After compression and condensation, the device transfers the refrigerant to a second set of spokes on the common shaft to expand the refrigerant, delivering it to the evaporator. The expansion process adds torque that contributes to the spin of the assembly.
- Depending on the configuration, the evaporator could also reside in axially oriented components that are aligned with the rotating central shaft,[92] and a shaft-mounted pre-compressor that could help modulate the device.[93]

Using the integrated assembly, the researchers believe the technology can improve energy efficiency of A/C systems by achieving isothermal compression and expansion with the spokes, while also decreasing manufacturing costs by reducing the number of components. The current prototypes are designed in a split-system configuration, but the researchers envision other equipment form factors, such as RTUs and PTACs. (Note: Simplified illustrations of the turbo-compressor-condenser-expander are unavailable at this time, but the technology patents provide figures of several variants.[94])

Technical Maturity and Current Developmental Status

Appollo Wind Technologies has developed several prototype iterations and is currently conducting testing of several prototypes at a third-party laboratory. If testing proves successful, the researchers plan to conduct field tests to demonstrate performance in various relevant conditions.[95]

Barriers to Market Adoption

There is limited information on performance and cost. The unique heat exchanger assemblies require specialized joining methods with uncertain manufacturability and long-term reliability. In addition, safety and/or noise may be a concern due to the high RPM of the metal assembly.

Energy Savings Potential

Potential Market and Replacement Applications

From a technical-fit standpoint, the technology could be used in any type of air-cooled packaged A/C system meant for commercial buildings.

Energy Savings

The researchers anticipate the performance of the current design, estimated at 20 SEER for the split-system prototypes, to be comparable to high-efficiency residential products on the market today. Other self-contained designs (e.g., PTACs) could achieve higher efficiencies by having all components on the common shaft, but these designs have not been tested yet.[96]

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[92] Swett, Peter. 2016. "Isothermal-turbo-compressor-expander-condenser-evaporator device." US Patent Application US20160138815A1. May 2016.
[93] Personal communication with Peter Swett. Appollo Wind Technologies. July 13, 2017.
[94] Swett, Peter. 2016. "Isothermal-turbo-compressor-expander-condenser-evaporator device." US Patent Application US20160138815A1. May 2016.
[95] Personal communication with Peter Swett. Appollo Wind Technologies. July 13, 2017.
[96] Ibid

Cost and Complexity

By combining several components into a single assembly on a common shaft, the researchers believe that the fully developed turbo-compressor-condenser-expander will have lower manufacturing cost. The technology is expected to have complexity and installation requirements that are similar to conventional A/C equipment.

Peak-Demand Reduction and Other Non-Energy Benefits

Peak-demand reduction would be as expected for the average level of energy savings. The technology appears to have the potential to achieve current A/C performance levels with CO_2 refrigerant in hot climates. The technology was originally developed for CO_2, but for current prototypes the researchers have focused on conventional refrigerants.[97]

Next Steps for Technology Development

Laboratory testing that is currently underway will further reveal the performance, reliability, and manufacturability of the turbo-compressor-condenser-expander technology, and will help determine its future for commercial A/C applications.

Table 24 lists potential next steps to advance the turbo-compressor-condenser-expander heat pump technology.

Table 24: Recommended Next Steps for the Development of Turbo-Compressor-Condenser-Expander Heat Pump

Activities
Conduct laboratory testing on the split-system prototypes, and if successful, conduct field testing in relevant applications
Work with major manufacturers and suppliers to determine production feasibility and costs relative to current equipment designs
Continue to develop advanced designs in which all components are integrated on the common shaft

[97] Ibid

5.6 Electrocaloric Cooling System

Brief Description	Specialized electrocaloric materials are oscillated in an electric field, which causes them to experience reversible temperature change and transfer heat.

Technology Characteristics	Value	Comments
Technology Category	Alternative Electrically Driven Heat Pump Technologies	
Technology Readiness Level (TRL)	Early Stage Research (TRL 1-2)	R&D to date has focused on material research, with few attempts at a bench-scale cooling device
Unit Energy Savings	25%	High COPs have been shown for small capacities and small temperature lifts
Technical Energy Savings Potential	248.3 TBtu	All vapor-compression type air cooling systems except chillers
Non-Energy Benefits	1-2 quantified benefits	Solid-state cooling cycle with lower noise and zero-GWP working fluids for reduced direct GHG emissions
Peak Demand Reduction Potential	Low	Peak-demand reduction would be as expected from the average level of energy savings
Relative Cost Premium	Significantly higher cost	Costs are largely unknown; the technology will use advanced materials that likely have high incremental cost
Operational Complexity	Neutral	Systems are projected to have similar operational complexity and reliability as conventional products

Background

Technology Description

Electrocaloric cooling systems are based on the electrocaloric effect, in which a dielectric material exhibits reversible temperature change when exposed to a change in electric field. Similar to magnetocaloric cooling (Section 5.8), under adiabatic conditions the material changes temperature when an electric field is applied and decreases temperature when the field is reduced. The microscopic mechanism involved relates to changes in the entropy of the material's dipoles without any change in the total entropy of the material.

By oscillating the electric field, and thus the material temperature, electrocaloric materials can be made to absorb heat from the conditioned space and then reject heat to a heat sink, operating as a heat pump cycle.[98] If successfully developed as a product, electrocaloric cooling systems could offer high COPs without the use of high GWP refrigerants.

Most systems under development use specially designed ceramic or polymer thin films that undergo

[98] (a) Cui et al. 2015. "Advancing Caloric Materials for Efficient Cooling: Key Scientific and Device-Related Materials Challenges for Impact." University of Maryland. December 2015. Available at: https://www.nanocenter.umd.edu/events/amec/2015.Workshop.Advancing_Caloric_Materials.REPORT.pdf; (b) Correia, T. and Zhang, Q., 2014. "Electrocaloric Effect: An Introduction," in: *Electrocaloric Materials: New Generation of Coolers*, Springer, Heidelberg, 2014.

temperature change in an electric field with a strength of 100-1,000 kV/cm. Researchers have developed a variety of system architectures for electrocaloric cooling systems. **Error! Reference source not found.** and REF _Ref491700086 \h * MERGEFORMAT **Error! Reference source not found.** provides two examples electrocaloric cooling concepts, with the major difference being how the electric field oscillates relative to the electrocaloric materials.

Figure 21 shows a concept involving a multi-chamber process, with a working fluid that is moved between the chambers by two spacers or pistons, plus a porous electrocaloric regenerator. This concept is similar to other solid-state heat pump cycles.

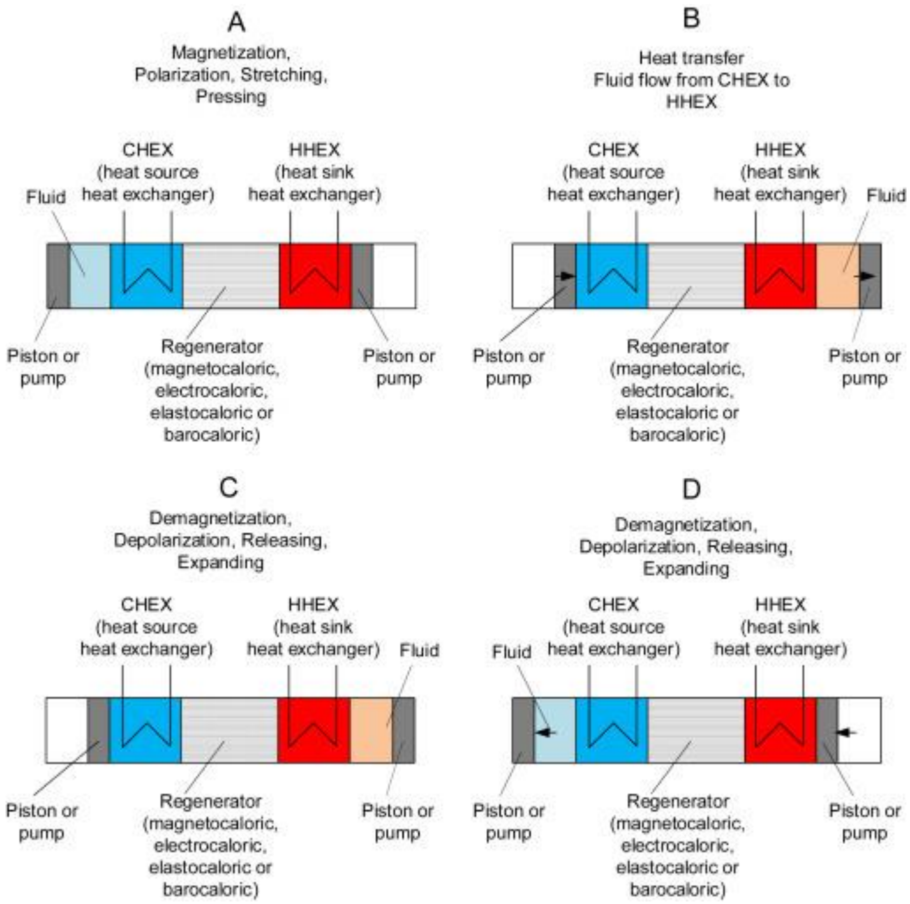

Figure 21: Schematic of active electrocaloric regeneration heat pump process

Source: Kitanovski et al. (2015)[99]

When the electric field is applied in process A, the electrocaloric material increases temperature. In process B, the working fluid is moved from the cold heat exchanger through the electrocaloric material, where it picks up heat and increases in temperature, thus being able to reject heat in the hot (heat sink) heat exchanger (HHEX). In process C, the electric field is removed, causing the electrocaloric material to decrease temperature. Finally, in the last process (D), the working fluid is pushed back through the regenerator, losing substantial heat to the electrocaloric material as it travels to the cold (heat source) heat exchanger, CHEX. When it reaches the CHEX, it is cold enough to absorb the heat load from it, thus providing space cooling for the building.[100]

[99] Kitanovski et al. 2015. "Present and Future Caloric Refrigeration and Heat-Pump Technologies." International Journal of Refrigeration. Volume 57. September 2015. Available at: http://www.sciencedirect.com/science/article/pii/S0140700715001759#fig2

[100] Aprea et al. 2016. "Electrocaloric Refrigeration: An Innovative, Emerging, Eco-friendly Refrigeration Technique." 34th UIT Heat Transfer Conference 2016. Available at: http://iopscience.iop.org/article/10.1088/1742-6596/796/1/012019/pdf

Researchers at UTRC have demonstrated 2.5 °C temperature difference with a benchtop prototype device using a similar piston-regenerator concept.[101]

Other electrocaloric systems maintain a constant electric field in a specific area and cyclically move the electrocaloric material through the charged area. Figure 22 provides a schematic of a rotary electrocaloric cooling system under development at Penn State University. The system consists of a stack of rings, separated into pairs (left image). Each pair of rings is thermally insulated from neighboring ring pairs. Each ring has many electrocaloric segments that are thermally separate from each other within the ring, but are in thermal contact with the corresponding element of other ring in the pair, i.e., directly above or below it. The rings of each pair rotate, in step-wise fashion, in opposite directions. After each shift in position, the ring pairs rest in place for a period of time to allow heat transfer to occur between the upper and lower segments.

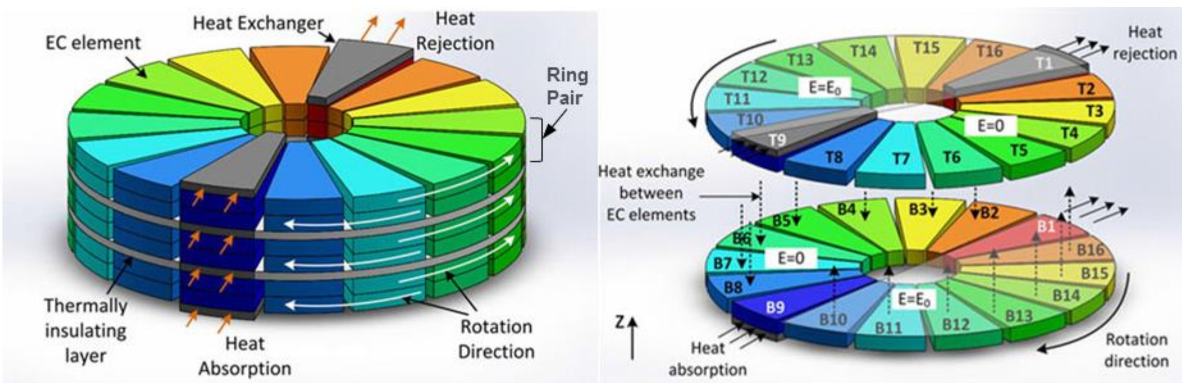

Figure 22: Schematic of rotary electrocaloric cooling system

Source: Gu (2014)[102]

At all times, the hottest segment in each ring is situated just above or below a heat-rejection heat exchanger, to which it releases heat. Similarly, the coldest segment is located just above or below a heat-absorption heat exchanger, from which it receives heat.

As illustrated in the right image, within each pair of rings an electric field ($E = E_o$) is applied to one-half of each ring. The geometry of the electric fields is such that for any given position, one ring's segment has a field of E_o and the corresponding segment of the other ring has no electric field. Under this arrangement, the temperature differences of ring segments result in heat flow from the segments with an electric field to the opposing zero-field segment in the ring pair, while at the same time the temperature of segments gets colder as they approach the heat-absorption heat exchanger and hotter as they approach the heat-rejection exchanger.

Consider the top ring. Each time the top ring segment at position T2 enters the electric field situated at the hot heat exchanger, its temperature increases and it will reject heat if its temperature is higher than the heat sink. The ring then rotates through the electric field and transfers heat to the lower ring, which is lower temperature since it is not in a field. When the top ring meets cold heat exchanger, the electric field ends and the ring segment's temperature will drop such that it can absorb heat from the cold heat exchanger. Because of the counterrotation and the oppositely applied electric fields, both rings undergo the temperature changes at the

[101] Annapragada, Ravi. 2017. "High-Efficiency Solid-State Heat Pump Module." 2017 Building Technologies Office Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/7_312111_Annapragada_031517-1430.pdf
[102] Gu, Haiming. 2014. "Chip-Scale Cooling Devices based on Electrocaloric Effect." Pennsylvania State University. August 2014. Available at: https://etda.libraries.psu.edu/files/final_submissions/9831

same time, for an overall increase in heat transfer capacity.[103] Researchers at PSU have demonstrated a 2°C temperature difference with a laboratory prototype of this type.[104]

Technical Maturity and Current Developmental Status

Electrocaloric cooling technologies are under development by various research organizations around the world, but the technology is in the early stages of development for building HVAC and other cooling applications. Most work to date has been analysis of potential electrocaloric materials and system architectures with small thermal capacity and temperature differences, aimed at small-scale electronics cooling applications.

Key to the advancement of the technology will be the continued development of high-performance electrocaloric materials and their integration into cooling systems.[105] To support this goal, the DOE Advanced Manufacturing Office (AMO) established the CaloriCool consortium[106] at Ames National Laboratory in 2016, to accelerate research into advanced materials for magnetocaloric (Section 5.8), electrocaloric (Section 5.6), elastocaloric (Section 5.3), and other solid-state cycles.[107]

Barriers to Market Adoption

Electrocaloric cooling systems could achieve wide adoption in building HVAC&R systems once they are fully developed. The technology requires long-term R&D to reach that state of development and to prove its effectiveness for cooling applications in buildings or other venues.

Energy Savings Potential

Potential Market and Replacement Applications

Electrocaloric cooling systems could be applied in all vapor-compression type air cooling systems for commercial buildings. We do not include chillers, as most research to date has focused on packaged HVAC applications. The technology could also operate as a reversible heat pump, but no information is available on space heating performance.

Energy Savings

Laboratory testing and simulations have shown electrocaloric cooling systems to have the potential for high COPs, but at capacities and temperature lifts too small for building cooling or refrigeration applications.[108] With support by DOE BTO, researchers at UTRC are currently developing a laboratory prototype for an electrocaloric cooling system that can provide a COP greater than six at more than 6°C temperature lift With continued improvement, the research team projects energy savings of 20% or greater, assuming >25% efficiency improvement.[109]

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[103] Gu, Haiming. 2014. "Chip-Scale Cooling Devices based on Electrocaloric Effect." Pennsylvania State University. August 2014. Available at: https://etda.libraries.psu.edu/files/final_submissions/9831
[104] Zyga, Lisa. 2017. "Electrocaloric Refrigerator Offers Alternative Way to Cool Everything from Food to Computers." Phys.org. June 2017. Available at: https://phys.org/news/2017-06-electrocaloric-refrigerator-alternative-cool-food.html
[105] Pecharsky, Vitalij. 2017. "Rethinking HVAC Technology to Meet Future Global Demand." R&D Magazine. July 2017. Available at: https://www.rdmag.com/article/2017/07/rethinking-hvac-technology-meet-future-global-demand
[106] CaloriCool - The Caloric Materials Consortium. Accessed August 2017. Available at: https://caloricool.org/
[107] DOE. 2016. "New AMO Consortium Focuses on Energy Efficient and Environmentally Friendly Materials for Cooling." March 2016. Available at: https://energy.gov/eere/amo/articles/new-amo-consortium-focuses-energy-efficient-and-environmentally-friendly-materials
[108] Guo et al. 2014. "Design and Modeling of a Fluid-Based Micro-Scale Electrocaloric Refrigeration System." International Journal of Heat and Mass Transfer. 2014. Available at: http://ntpl.me.cmu.edu/pubs/guo_ijhmt14_ece.pdf
[109] Annapragada, Ravi. 2017. "High-Efficiency Solid-State Heat Pump Module." 2017 Building Technologies Office Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/7_312111_Annapragada_031517-1430.pdf

Cost and Complexity

Electrocaloric cooling systems are expected to have operational complexity and reliability similar to conventional HVAC equipment. The systems will require a secondary working fluid to transfer heat to and from the electrocaloric assembly. Costs are largely unknown, but the technology uses advanced materials that are likely to have high incremental cost until volumes reach a high level.

Peak-Demand Reduction and Other Non-Energy Benefits

Peak-demand reduction would be as expected for the average level of energy savings. Similar to other solid-state technologies, electrocaloric cooling systems are expected to offer lower noise and vibration by eliminating the compressor. The technology does not use any high-GWP refrigerants, and it will likely use water or other zero-GWP working fluids to transfer heat.

Next Steps for Technology Development

Electrocaloric cooling systems have shown promising performance and efficiency in limited laboratory research. However, the technology requires material breakthroughs from R&D programs like CaloriCool to reach the point of feasibility for building HVAC systems.

Table 25 lists potential next steps to advance electrocaloric cooling systems.

Table 25: Recommended Next Steps for the Development of Electrocaloric Cooling Systems

Activities
Continue research to better understand the electrocaloric properties of different polymers, ceramics, and other materials
Integrate advanced electrocaloric materials into cooling system designs for laboratory testing
Develop full-scale prototypes that prove the ability of electrocaloric technology to handle larger loads

5.7 Electrochemical Heat Pump

Brief Description	An electrochemical cell using a proton exchange membrane compresses a hydrogen working fluid to drive a vapor-compression or metal-hydride heat pump cycle.

Technology Characteristics	Value	Comments
Technology Category	Alternative Electrically Driven Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	Laboratory prototypes of components have been developed
Unit Energy Savings	20%	R&D efforts underway target COP of >4 for space cooling
Technical Energy Savings Potential	198.6 TBtu	All commercial A/C systems, except chillers
Non-Energy Benefits	1-2 quantified benefits	Low noise operation and the ability to use zero-GWP refrigerants for reduced direct GHG emissions
Peak Demand Reduction Potential	Low	Peak demand reduction would be as expected from average level of energy savings
Relative Cost Premium	Moderately higher upfront cost	Cost premium expected to be modest so that quick payback can be achieved
Operational Complexity	Neutral	Unknown for commercial-ready products, but expected to operate in a similar manner as conventional systems

Background

Technology Description

The vast majority of commercial A/C systems use some form of electromechanical compressor (e.g., scroll, screw, centrifugal) to raise the pressure of the refrigerant and drive the cooling cycle. In place of a motor-driven compressor, electrochemical compressors raise the pressure of a hydrogen working fluid using an electrochemical cell with a proton exchange membrane, supplied by an electricity source. Figure 23 illustrates the basic operation of an electrochemical compressor. The technology uses components similar to those in a fuel cell system. Voltage is applied to the system (rather than being generated by it, as in a fuel cell), which separates low-pressure hydrogen gas into its proton and electron components at the anode. The protons pass through the polymer electrolyte membrane, while the electrons travel through the electrical circuit, where they reconnect with the protons at the cathode to regenerate hydrogen gas. This electrochemical process drives hydrogen through the cell, which increases the pressure of the hydrogen contained within the closed system, thus acting as a compressor.

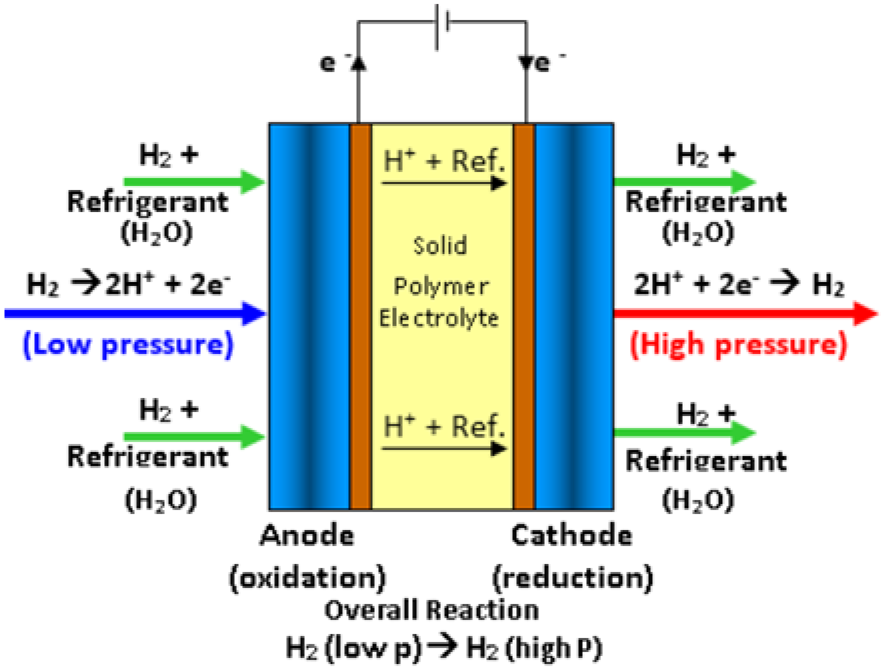

Figure 23: Electrochemical compressor diagram

Source: Bahar (2016)[110]

Electrochemical compressors offer the potential for higher energy efficiency than electromechanical compressors, as well as low-noise operation and the use of environmentally benign refrigerants. As part of a heat pump cycle, the hydrogen gas is combined with water or another refrigerant. The hydrogen pressurization raises system pressure and drives the combined working fluid through the condenser, expansion valve, and evaporator of a standard vapor-compression heat pump cycle. Alternatively, the system can drive several alternative heating or cooling cycles, such as a metal-hydride heat pump, where hydrogen gas is the primary working fluid.[111,112]

Technical Maturity and Current Developmental Status

Heat pumps using electrochemical compressors are still undergoing laboratory R&D and initial prototype testing, but face a number of significant challenges before commercial introduction. BTO and others have supported Xergy Inc.[113] in the development of electrochemical compression systems for HVAC[114] and water

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[110] Bahar, Bamdad. 2016. "Low-Cost Electrochemical Compressor Utilizing Green Refrigerants for HVAC Applications." 2016 Building Technologies Office Peer Review. April 2016. Available at: https://www.energy.gov/sites/prod/files/2016/04/f30/312110_Bahar_040616-1105.pdf
[111] Tao et al. 2015. "Electrochemical Compressor Driven Metal Hydride Heat Pump." International Journal of Refrigeration. 2015. Available at: http://www.cswang.umd.edu/publications/papers/YeTao.pdf
[112] Abdelaziz, Omar. 2017. "Development of Separate Sensible and Latent Cooling System using Electrochemical Compressor." ORNL. 12th IEA Heat Pump Conference. 2017. Available at: http://hpc2017.org/wp-content/uploads/2017/06/o493.pdf
[113] Xergy Inc. Accessed August 2017. Available at: https://www.xergyinc.com/
[114] DOE. 2017. "Low-Cost Electrochemical Compressor Utilizing Green Refrigerants for HVAC Applications." Accessed August 2017. Available at: https://www.energy.gov/eere/buildings/downloads/low-cost-electrochemical-compressor-utilizing-green-refrigerants-hvac

heating applications[115] using water, CO_2, and other refrigerants. Current efforts focus on developing a room A/C (~0.5 ton) with a COP greater than four.[116]

Barriers to Market Adoption

The most significant barrier to market adoption is the development of a commercially available and cost-effective product. The electrochemical compressors themselves are smaller than conventional compressors, but the size required for other system components to accommodate the alternative refrigerants is unknown. The introduction of new working fluids to the HVAC industry requires significant R&D effort. In addition, the use of hydrogen gas may pose issues with building codes and public acceptance.

Energy Savings Potential

Potential Market and Replacement Applications

Electrochemical heat pumps could technically replace have the potential to replace most vapor-compression type HVAC systems, but their development for different applications will depend on the technologies advantages in specific markets. Initial product development has focused on packaged A/C systems

Energy Savings

Full-scale prototypes are currently under development, with researchers projecting COPs of four or higher.[117] We conservatively estimate energy savings of 20% for commercial A/C systems.

Cost and Complexity

The incremental cost of the electrochemical compressor itself is expected to be modest, but it is uncertain how the cost for an entire system would compare to conventional equipment. Similarly, electrochemical heat pump systems are expected to operate in a similar manner as conventional systems, however the full system's size, weight, reliability, and other characteristics are still unknown.

Peak-Demand Reduction and Other Non-Energy Benefits

Electrochemical compressors are suitable for a wide variety of working fluids, including natural refrigerants with zero-GWP. The systems should have lower noise than systems using electromechanical compressors. Peak demand reduction would be as expected from average level of energy savings.

Next Steps for Technology Development

Electrochemical heat pumps are a potentially groundbreaking change for commercial A/C systems, but long-term R&D is necessary to better understand its potential energy savings, operational performance, and cost-effectiveness and, ultimately, bring the technology to market. Even with high compressor efficiencies, inefficiencies in the rest of the cycle may limit overall system performance. If current laboratory testing on small-capacity prototypes is successful, researchers should pursue full-scale A/C prototypes for laboratory and field demonstrations.

Table 26 presents the potential next steps to advance electrochemical heat pumps.

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[115] DOE. 2017. "Advanced Hybrid Water Heater using Electrochemical Compressor." Accessed August 2017. Available at: https://www.energy.gov/eere/buildings/downloads/advanced-hybrid-water-heater-using-electrochemical-compressor

[116] Bahar, Bamdad. 2017. "Low-Cost Electrochemical Compressor Utilizing Green Refrigerants for HVAC Applications." 2017 Building Technologies Office Peer Review. April 2017. Available at: Available at: https://www.energy.gov/sites/prod/files/2017/04/f34/8_312110_Bahar_031517-1500.pdf

[117] Ibid

Table 26: Recommended Next Steps for the Development of Electrochemical Heat Pumps

Activities
Continue laboratory R&D and testing for different electrochemical compressor designs, heat pump cycles, working fluids, etc.
Develop full-scale prototypes for further laboratory and field testing to understand the manufacturing and operational challenges for electrochemical heat pumps

5.8 Magnetocaloric Cooling System

Brief Description	A system in which specialized magnetocaloric materials are cyclically exposed to a changing magnetic field, creating a reversible temperature change in the material that drives the cooling cycle.

Technology Characteristics	Value	Comments
Technology Category	Alternative Electrically Driven Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	Initial prototypes for space cooling under development. Technology is closest to commercialization for small self-contained refrigeration applications
Unit Energy Savings	20%	Estimated 20% energy savings for A/C applications, savings up to 40-50% projected for refrigeration applications
Technical Energy Savings Potential	198.6 TBtu	All vapor-compression type air cooling systems except chillers
Non-Energy Benefits	1-2 quantified benefits	Projected to have lower noise than compressor-based systems. Systems use working fluids with zero-GWP for reduced direct GHG emissions
Peak Demand Reduction Potential	Low	Peak-demand reduction would be as expected from average level of energy savings
Relative Cost Premium	Moderately higher upfront cost	Unknown for A/C applications, but supermarket refrigeration technology developers project 1-5 year paybacks in Europe
Operational Complexity	Neutral	Systems are projected to have similar operational complexity and reliability to conventional products

Background

Technology Description

Magnetocaloric cooling systems use the unique properties of materials that undergo a reversible temperature change when exposed to a changing magnetic field. These paramagnetic materials increase temperature when magnetized and decrease temperature when demagnetized. By cyclically altering the magnetic state of the materials, the system functions similar to a conventional cooling cycle, absorbing heat from the conditioned space, then rejecting heat to a heat sink. If magnetocaloric cooling systems are successfully developed, they could offer potential energy savings for space cooling and refrigeration applications without the use of high GWP refrigerants.

Researchers have studied the magnetocaloric effect since its discovery in 1917, however R&D on using the effect in thermodynamic cycles only began in the 1960s. Efforts to develop prototypes for HVAC&R applications are even more recent. Figure 24 and Figure 25 illustrates two magnetocaloric cooling systems under development today for small, self-contained commercial refrigeration and building space cooling applications. Figure 24 shows a refrigeration concept under development by Cooltech Applications that uses a series of magnetic disks that rotate around an magnetocaloric material (MCM) heat exchange assembly. As the magnets rotate they magnetize and demagnetize the MCM heat exchangers, which transfer heat to and from the water-based heat transfer fluid. The fluid is pumped to the evaporator to cool the space, or to the condenser to reject heat, depending on the positions of the magnetic disks.

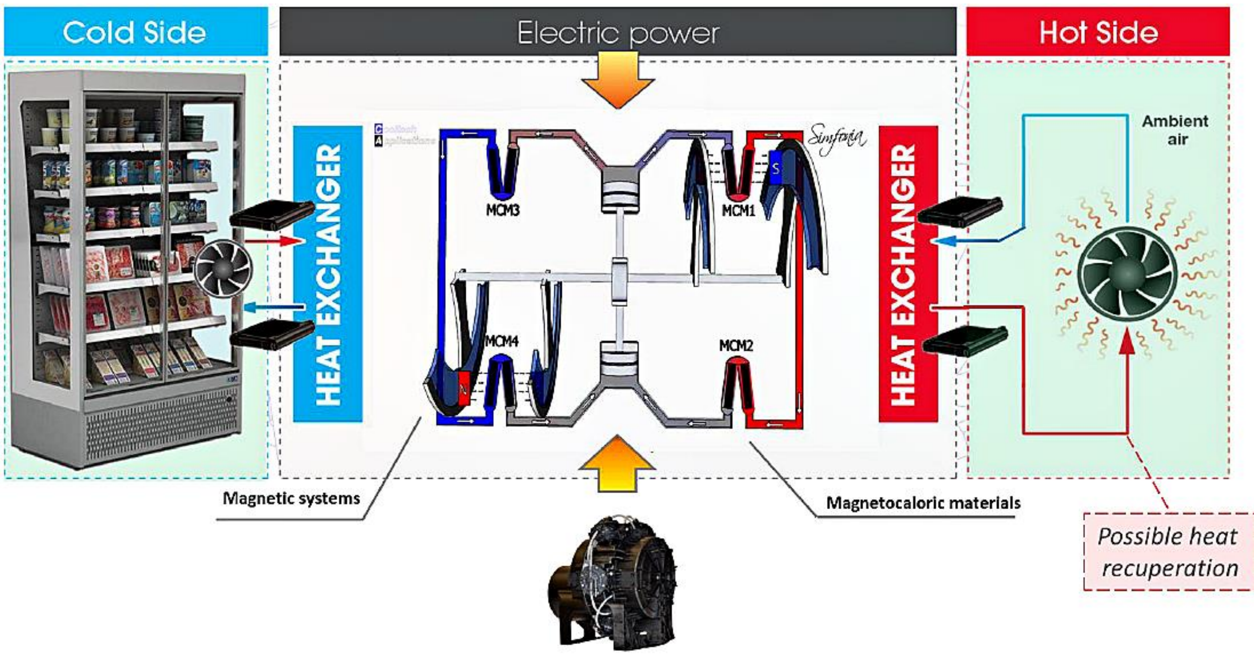

Figure 24: Schematic of fluid-based magnetic cooling concept

Source: Cooltech (2013)[118]

Figure 25 provides a schematic of a solid-state magnetic cooling system under development by ORNL for A/C applications. In place of pumping fluid through the MCM heat exchangers, this design moves a series of high conductivity metal rods or sheets through the MCM assembly to rapidly transfer heat to and from the assembly when it is cyclically magnetized and demagnetized. The rods or sheets would then transfer heat to secondary fluid loops for space cooling and heat rejection. Due to the higher conductivity of the metal rods or sheets compared to water, this concept could operate at higher frequency (5 Hz vs. 2 Hz) and achieve greater capacity and efficiency than the water-based concept of Figure 24.[119] However, metal-to-metal contact requires attention to be paid to friction and contact resistance issues.

[118] Cooltech Applications. 2016. "Company Presentation." May 2016. Available at: http://www.cooltech-applications.com/presentation-document.html

[119] Zhang et al. 2016. "Preliminary Analysis of a Fully Solid State Magnetocaloric Refrigeration." Available at: http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2757&context=iracc

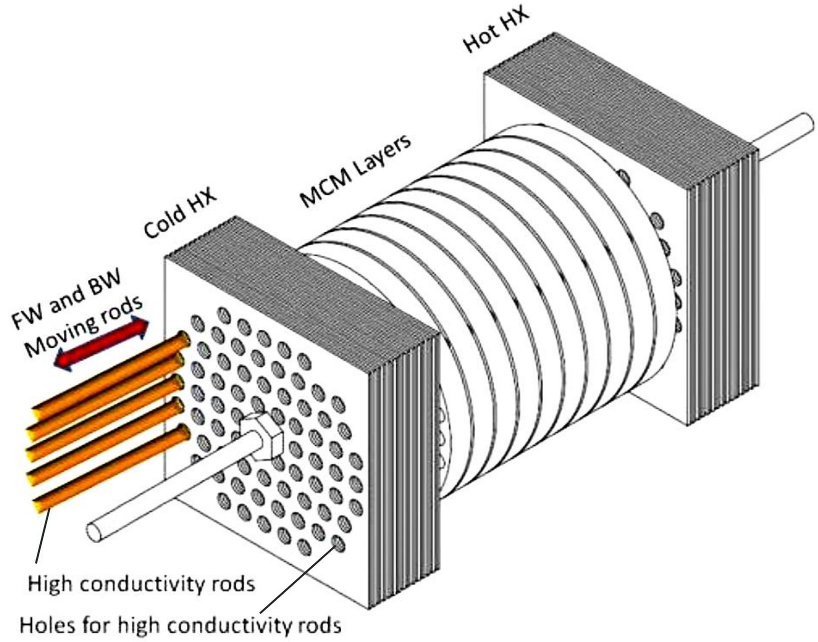

Figure 25: Schematic of solid-state magnetic cooling concept

Source: Abu-Heiba (2017)[120]

Technical Maturity and Current Developmental Status

Magnetic cooling systems have been researched for several decades at Ames National Laboratory and other organizations,[121] with products nearing commercialization for small-scale refrigeration applications. These include the following:

- GE and ORNL have developed several benchtop prototypes for a residential refrigerator under a Collaborative Research and Development Agreement (CRADA).[122]
- The appliance manufacturer Haier has debuted a wine cooler (45-52°F, 8-12°F), developed with Astronautics Corporation of America and the chemical company BASF.[123]
- Cooltech Applications has developed a magnetocaloric refrigerator for the medical and commercial refrigeration market with a performance of 400 W and 5°C cabinet temperature.[124] The European retailer Carrefour is conducting field testing on Cooltech's beverage merchandiser product.[125]

[120] Abu-Heiba, Ahmad. 2017. "Non-Vapor Compression – Solid State Magnetic Cooling." ORNL. 2017 Building Technologies Office Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/6_312112_Abu-Heiba_031517-1400.pdf
[121] Karsjen, Steve. 2009. "Room-Temperature Magnetic Refrigeration." The Ames Laboratory. September 2009. Available at: https://www.ameslab.gov/files/MagFridge_Foundation.pdf
[122] Momen, Ayyoub. 2017. "Magnetocaloric Refrigerator Freezer." ORNL. 2017 Building Technologies Office Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/2_32226a_Momen_031317-1400.pdf
[123] BASF. 2015. "Premiere of Cutting-Edge Cooling Appliance at CES 2015." January 2015. Available at: https://www.basf.com/en/company/news-and-media/news-releases/2015/01/p-15-100.html
[124] Cooltech Applications Website. Accessed August 2017. Available at: http://www.cooltech-applications.com/
[125] Cooling Post. 2016. "Carrefour to Test Magnetic Refrigeration." September 2016. Available at: http://www.coolingpost.com/world-news/carrefour-to-test-magnetic-refrigeration/

- Camfridge is developing a magnetic refrigerator for residential applications, under collaboration with the major appliance manufacturers Beko, Whirlpool, and others.[126]
- Under support from DOE BTO, ORNL is currently developing a solid-state magnetic cooling concept for space cooling purposes (Figure 25). The current window A/C system prototype is anticipated to have a cooling capacity of 500 W.[127]

Key to the advancement of the technology will be the continued development of high-performance paramagnetic materials and their integration into cooling systems.[128] To support this goal, the DOE AMO established the CaloriCool consortium[129] at Ames National Laboratory in 2016 to accelerate research into advanced materials for magnetocaloric, electrocaloric (Section 5.6), elastocaloric (Section 5.3), and other solid-state cycles.[130]

Barriers to Market Adoption

Magnetic cooling systems could achieve wide adoption in building HVAC&R systems, once they are fully developed, but the technology has encountered significant issues related to materials and system assembly. Developing compact, high-capacity systems at reasonable cost is needed for magnetocaloric space cooling systems to be commercially viable. Prices of the rare earth magnets used in current prototypes spiked in the early 2010s and, although they have substantially subsided since then, they may pose an issue in future years.[131]

Energy Savings Potential

Potential Market and Replacement Applications

Magnetic cooling systems could be used in all vapor-compression type air cooling systems for commercial buildings. We do not include chillers, as most research to date has focused on packaged HVAC and refrigeration applications. The technology could also operate as a reversible heat pump, but limited information is available on space heating performance.

Energy Savings

ORNL researchers project approximately 20% energy savings for their design under development for A/C applications.[132,133] Other organizations commercializing magnetic refrigerators project energy savings from

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[126] Camfridge Website. Accessed August 2017. Available at: http://www.camfridge.com/
[127] Abu-Heiba, Ahmad. 2017. "Non-Vapor Compression – Solid State Magnetic Cooling." ORNL. 2017 Building Technologies Office Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/6_312112_Abu-Heiba_031517-1400.pdf
[128] Pecharsky, Vitalij. 2017. "Rethinking HVAC Technology to Meet Future Global Demand." R&D Magazine. July 2017. Available at: https://www.rdmag.com/article/2017/07/rethinking-hvac-technology-meet-future-global-demand
[129] CaloriCool - The Caloric Materials Consortium. Accessed August 2017. Available at: https://caloricool.org/
[130] DOE. 2016. "New AMO Consortium Focuses on Energy Efficient and Environmentally Friendly Materials for Cooling." March 2016. Available at: https://energy.gov/eere/amo/articles/new-amo-consortium-focuses-energy-efficient-and-environmentally-friendly-materialsAvailable at: https://caloricool.org/
[131] Lovins, Amory. 2017. "Clean Energy and Rare Earths: Why Not to Worry." Bulletin of the Atomic Scientists. May 2017. Available at: http://thebulletin.org/clean-energy-and-rare-earths-why-not-worry10785
[132] Abu-Heiba, Ahmad. 2017. "Non-Vapor Compression – Solid State Magnetic Cooling." ORNL. 2017 Building Technologies Office Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/6_312112_Abu-Heiba_031517-1400.pdf
[133] Zhang et al. 2016. "Preliminary Analysis of a Fully Solid State Magnetocaloric Refrigeration." Available at: http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2757&context=iracc

20%[134] to 50%[135] for small commercial refrigeration applications. Further advancements are necessary for the initial commercialized products to meet the capacity and temperature requirements of commercial A/C systems.

Cost and Complexity

Magnetic cooling systems are expected to have similar operational complexity and reliability to conventional HVAC equipment. The systems will require secondary working fluids to transfer to and from the magnetocaloric assembly. With initial prototypes under development, equipment costs for A/C applications are unknown. Camfridge projects payback periods of 1-5 years for supermarket refrigeration applications in European markets.[136]

Peak-Demand Reduction and Other Non-Energy Benefits

Peak-demand reduction would be as expected from the average level of energy savings. By eliminating the compressor, magnetic cooling systems are expected to offer lower noise and vibration than conventional products. The technology uses solid-state magnets and other materials to generate cooling without the use of high-GWP refrigerants.

Next Steps for Technology Development

The near-term market introduction of magnetic cooling systems for small refrigeration applications is a promising sign that the technology may have wider potential. Nevertheless, additional R&D is necessary to increase the temperature lift, cooling capacity, and efficiency of conventional A/C systems. Beyond cooling performance, magnetic cooling systems must also meet the cost, size, weight, and reliability requirements of mature vapor-compression A/C products.

Table 27 lists potential next steps to advance magnetic cooling systems.

Table 27: Recommended Next Steps for the Development of Magnetic Cooling Systems

Activities
Continue to develop laboratory prototypes of magnetic cooling systems for A/C applications
Continue research into higher efficiency magnets and MCMs with a larger paramagnetic effect for use in future magnetic cooling systems
Conduct laboratory and field testing with available prototypes to further understand their performance for building A/C systems

[134] GE. 2014. “From Ice Blocks to Compressors to Magnets: The Next Chapter in Home Refrigeration.” March 13, 2014. Available at: http://pressroom.geappliances.com/news/from-ice-blocks-to-compressors-to-magnets:-the-next-chapter-in-home-refrigeration

[135] Delecourt, Vincent. 2017. “Magnetic Refrigeration.” ATMOsphere Japan. February 2017. Available at: http://www.atmo.org/media.presentation.php?id=979

[136] Ibid

6 Alternative Gas-Fired Heat Pump Technologies

Alternative Gas-Fired Heat Pump Technologies provide heating or cooling more efficiently, using a thermally activated heat pump cycle and use natural gas as the primary energy input. Table 28 provides a brief description and final ranking for the selected high priority technology options within the Alternative Gas-Fired Heat Pump Technologies category.

Table 28: Brief Descriptions for Alternative Gas-Fired Heat Pump Technologies

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Vuilleumier Heat Pump (6.1)	The system uses a gas-fired heat engine to operate a cylinder assembly that compresses and expands a refrigerant within several chambers, transferring heat with hydronic loops in the building.	Technology Development (TRL 3-4)	0.84	3.95
Ejector Heat Pump (6.2)	Specially designed nozzles drive a heat pump cycle by transferring energy from a high-pressure motive fluid to a secondary refrigerant.	Technology Development (TRL 3-4)	1.01	3.65
Fuel Cell Combined Cooling, Heating, and Power System (6.3)	The packaged system provides both space cooling and electric power to buildings by utilizing the waste heat from a natural gas fuel cell to operate an evaporative liquid-desiccant cooling cycle.	Technology Demonstration (TRL 5-6)	0.37	3.15

6.1 Vuilleumier Heat Pump

Brief Description	The system uses a gas-fired heat engine to operate a cylinder assembly that compresses and expands a refrigerant within several chambers, transferring heat with hydronic loops in the building.

Technology Characteristics	Value	Comments
Technology Category	Alternative Gas-Fired Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	Prototypes under development for initial laboratory and field testing
Unit Energy Savings	50% Heating	Estimated 50% space heating savings over baseline natural gas furnace; primary energy consumption for space cooling is comparable
Technical Energy Savings Potential	858.1 TBtu	All commercial gas furnace and boiler heating
Non-Energy Benefits	Potential for significant benefits, but not well documented	Low-GWP working fluids can reduce direct GHG emissions
Peak Demand Reduction Potential	High	Space cooling from gas-fired system has large peak demand benefits
Relative Cost Premium	Moderately higher upfront cost	Unknown cost, but expected to be higher than traditional systems
Operational Complexity	Neutral	Operations and complexity of the combined heat pump could be comparable to traditional systems

Background

Technology Description

The Vuilleumier heat pump (VHP) is a gas-fired heat pump technology that has the potential to reduce commercial building energy consumption associated with HVAC and water heating, particularly in cold climates. The technology operates similarly to a duplex Stirling cycle where a gas-fired heat engine provides the motive force for the heat pump. Figure 26 provides an illustration of the VHP under development by ThermoLift.[137] A specialized gas burner drives the heat engine and heat pump cycles by oscillating two displacers within a cylinder to move a helium refrigerant between three chambers. The motion of the displacers compresses and expands the refrigerant, creating the temperature differentials in the hot, warm, and cold chambers. Heat exchangers then transfer heat to/from hydronic loops for use within the building. Through this process, the VHP can offer primary energy savings by achieving relatively high heating and cooling COPs (estimated 1.6 COP heating, 1.0 COP cooling) using natural gas rather than electricity. In addition, the technology maintains efficient heating performance at low ambient temperatures (estimated 1.3 COP at -15°F), which is a target for cold-climate applications.[138]

[137] ThermoLift Website. Accessed August 2017. Available at: http://www.tm-lift.com/
[138] Schwartz, Paul. 2016. "The Natural Gas Heat Pump and Air Conditioner." ThermoLift. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/31290_Schwartz_040616-1705.pdf

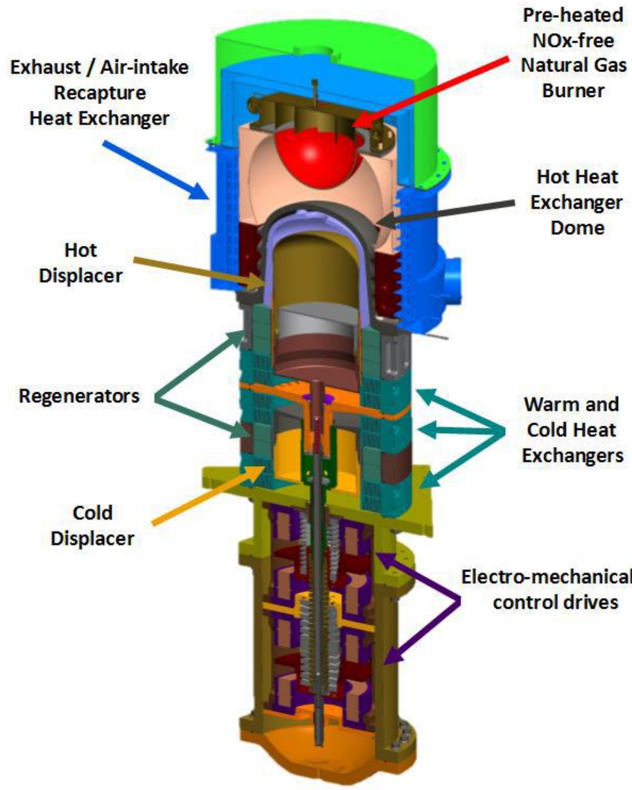

Figure 26: Cutaway view of ThermoLift VHP

Source: Schwartz (2016)[139]

The heat pump would have several hydronic loops connecting with an external air-source heat exchanger, internal heat exchangers, and thermal storage systems (e.g., a hot water tank) to provide space heating, space cooling, and water heating. Figure 27 provides a schematic for the VHP in a residential application.

[139] Ibid

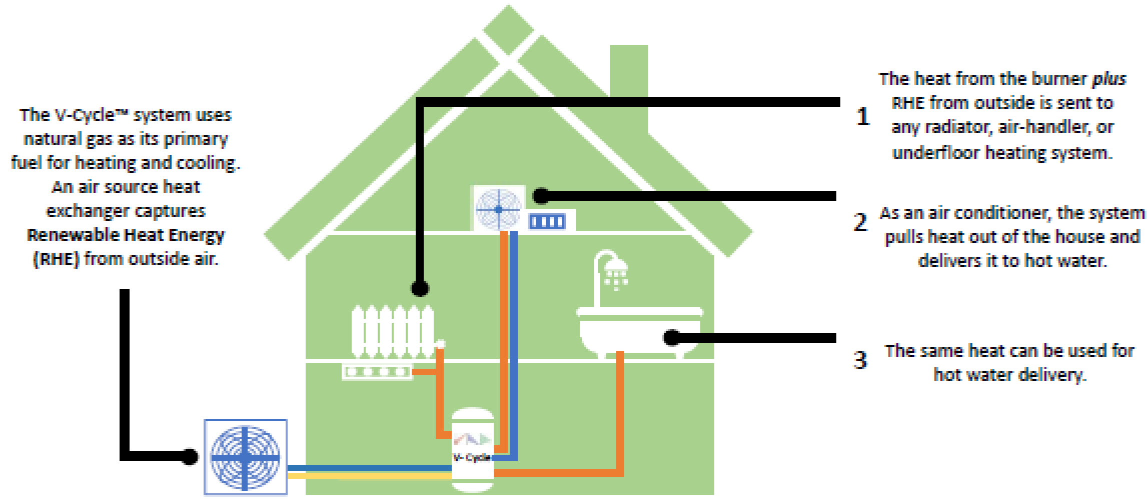

Figure 27: Schematic of ThermoLift VHP in residential application

Source: Schwartz (2016)[140]

Technical Maturity and Current Developmental Status

Research organizations have investigated VHPs for different applications since the 1960s, including NASA, Sanyo, Bosch-Viessmann Energie, but the start-up ThermoLift has developed the technology for residential and commercial buildings since 2012.[141] The ThermoLift researchers have demonstrated the thermodynamic concept and core VHP technologies and are currently developing a next-generation prototype for laboratory and field testing with a target capacity of 25 kW heating and 12 kW cooling (85 kBtu/hr. / 3.5 tons).[142]

Barriers to Market Adoption

Beyond continued product development and commercialization, a major barrier will be incorporating hydronic loops into building infrastructure. In addition, in warmer climates with high space cooling demands, the technology may not achieve high primary energy savings. However, users could still realize utility cost savings due to low natural gas rates and peak demand benefits.

Energy Savings Potential

Potential Market and Replacement Applications

Once developed, VHPs could be technically suitable for most light-commercial HVAC and water heating applications. The current prototypes have a split-system hydronic configuration, but future designs could target the RTU market.

[140] Schwartz, Paul. 2016. "ThermoLift – V-Cycle Thermal Energy System." ThermoLift. 2016. Available at: https://higherlogicdownload.s3.amazonaws.com/APGA/c7dbaef7-f46e-4280-beee-7e00bd8e94a6/UploadedImages/2016%20Savannah/2016%20MSTTC/ThermoLift_Paul%20Schwartz.pdf
[141] Convey and Schwartz. 2015. "Modernizing the Vuilleumier Cycle: Recent Developments for a Novel Natural Gas Air-Conditioner and Heat Pump." IEA Heat Pump Centre. Vol. 33, No. 4. November 2015. Available at: http://heatpumpingtechnologies.org/publications/modernizing-the-vuilleumier-cycle-recent-developments-for-a-novel-natural-gas-air-conditioner-and-heat-pump/
[142] Schwartz, Paul. 2016. "The Natural Gas Heat Pump and Air Conditioner." ThermoLift. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/31290_Schwartz_040616-1705.pdf

Energy Savings

ThermoLift projects 30-50% reduction in HVAC energy consumption and utility cost, depending on climate and application.[143] Assuming 1.6 COP for space heating, VHPs would provide 50% energy savings over an 80% gas furnace or boiler. At 1.0-1.1 COP for space cooling, VHPs would have comparable cooling efficiencies to a light-commercial A/C on a primary energy basis. (Note – these estimates do not include parasitic energy consumption for fans or pumps.[144])

Cost and Complexity

ThermoLift expects their VHP to have comparable or favorable cost compared to conventional HVAC and water heating systems, but additional product development is needed to understand product and installation costs. Current estimates for the residential HVAC and water heating appliance are $5,500, compared to a combined cost for conventional HVAC and water heating systems of $8,500-$13,500.[145] As noted previously, the VHP uses several hydronic loops which may increase installation complexity for some applications.

Peak-Demand Reduction and Other Non-Energy Benefits

As a gas-fired cycle, the VHP technology would provide significant peak and overall demand savings for space cooling applications. The cycle uses the natural refrigerant helium as a working fluid in place of synthetic HFC or alternative refrigerants.

Next Steps for Technology Development

VHPs offer a promising opportunity to provide gas-fired space heating with thermal efficiency above 100%, especially in cold climate applications. The attractiveness of the technology will depend on further technology development and field trials that demonstrate the performance, efficiency, reliability, and other relevant attributes in residential and commercial building applications.

Table 29 presents the potential next steps to advance Vuilleumier heat pumps.

Table 29: Recommended Next Steps for the Development of Vuilleumier Heat Pumps

Activities
Continue development of laboratory prototypes to benchmark space-heating, space-cooling, and service-water-heating COPs and understand the parasitic energy consumption
Conduct field demonstrations in different building applications and climates to quantify the potential energy and cost savings, and build understanding for the reliability and installation requirements of the products
Develop performance models to predict the benefits and simple payback of HVAC and water heating savings for different applications and climates relative to conventional alternatives

143 Schwartz, Paul. 2017. "ThermoLift Executive Summary." February 2017. Available at: http://tm-lift.com/files/ThermoLift-ExecutiveSummary.pdf

144 Schwartz, Paul. 2016. "The Natural Gas Heat Pump and Air Conditioner." ThermoLift. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/31290_Schwartz_040616-1705.pdf

145 Schwartz, Paul. 2016. "ThermoLift – V-Cycle Thermal Energy System." ThermoLift. 2016. Available at: https://higherlogicdownload.s3.amazonaws.com/APGA/c7dbaef7-f46e-4280-beee-7e00bd8e94a6/UploadedImages/2016%20Savannah/2016%20MSTTC/ThermoLift_Paul%20Schwartz.pdf

6.2 Ejector Heat Pump

Brief Description	Specially designed nozzles drive a heat pump cycle by transferring energy from a high-pressure motive fluid to a secondary refrigerant.

Technology Characteristics	Value	Comments
Technology Category	Alternative Gas-Fired Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	Laboratory prototypes and modeling
Unit Energy Savings	27%	Space heating COP 1.1 vs. 0.80 for conventional gas-fired systems.
Technical Energy Savings Potential	463.4 TBtu	Gas-fired commercial furnaces and boilers
Non-Energy Benefits	Provides few or no benefits	Potential for space cooling with low-GWP refrigerants for reduced direct GHG emissions, but this is primarily a space heating technology
Peak Demand Reduction Potential	High	Significant peak demand reduction because space cooling would be supplied by natural gas or other heating source, rather than electricity
Relative Cost Premium	Moderately higher upfront cost	Cost is unknown, but upfront cost is expected to be higher
Operational Complexity	Moderately higher complexity	Potentially larger equipment sizes. Potentially higher installation complexity if in GSHP configuration.

Background

Technology Description

Ejectors are specially designed nozzle components in mechanical fluid processes that utilize a high-pressure motive or driving fluid to accelerate and entrain a secondary fluid. Without any moving parts, the hot, high-pressure primary fluid can act as a compressor to raise the pressure of the secondary fluid. When applied to a refrigeration cycle, ejectors can act as a compression or expansion device in place of standard components, and they can drive a heat pump cycle. Figure 28 shows a basic outline of a steam ejector system. These types of ejector systems were common in early refrigeration applications due to their simple design, but the low cooling efficiencies (30%) limit their applicability, except where high-quality waste heat is available.

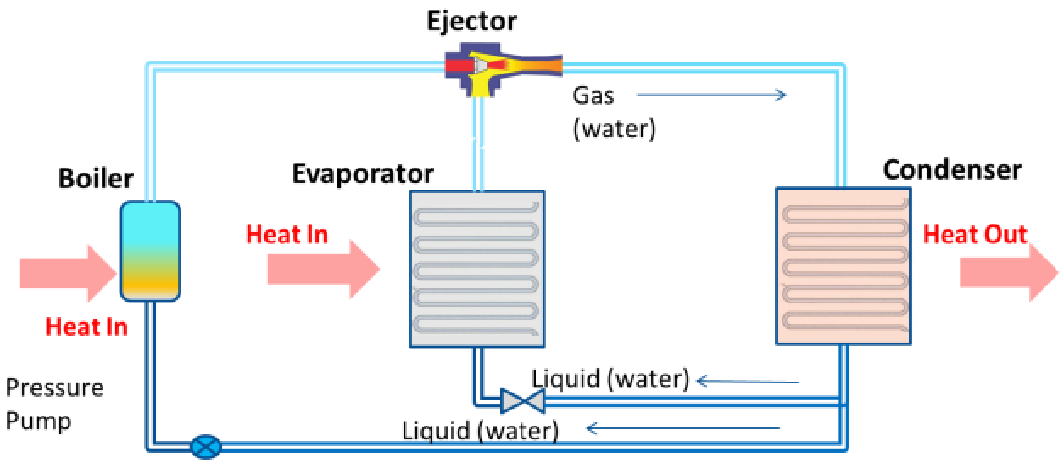

Figure 28: Steam ejector heat pump system

Source: Glanville (2014)[146]

Several organizations have extended the capabilities of ejector heat pumps to include space heating for different residential and commercial applications. In particular, May-Ruben Thermal Solutions have developed a binary fluid ejector concept that uses an optimized pair of refrigerant fluids, a fractionating condenser, and specially designed nozzles to achieve higher efficiencies.[147] Current modeling research suggests the gas-fired ejector heat pump could achieve COPs of 2.0 for space heating and 1.0 for space cooling.[148] Figure 29 provides a schematic of the binary fluid ejector system.

[146] Glanville, Paul. 2014. "Industrial Heat Pumps in Agricultural Drying Applications." GTI. International Gas Union Research Conference. September 2014.
Available at: http://members.igu.org/old/IGU%20Events/igrc/igrc-2014/presentations/to6-3_glanville_draft.pdf
[147] May-Ruben Technologies. 2014. "Binary Fluid Ejector." Accessed August 2017. Available at: http://may-rubentechnologies.com/index.php?option=com_content&view=article&id=64&Itemid=115
[148] Kooy, Rich. 2016. "Thermally-Driven Ground-Source Heat Pump." Utilization Technology Development. Research Project Summaries. 2015-2016 Project No. 1.14.G. Summary Report. Available at: https://www.utd-co.org/Documents/UTD-Annual-Report-Project-Summaries-2015-2016.pdf

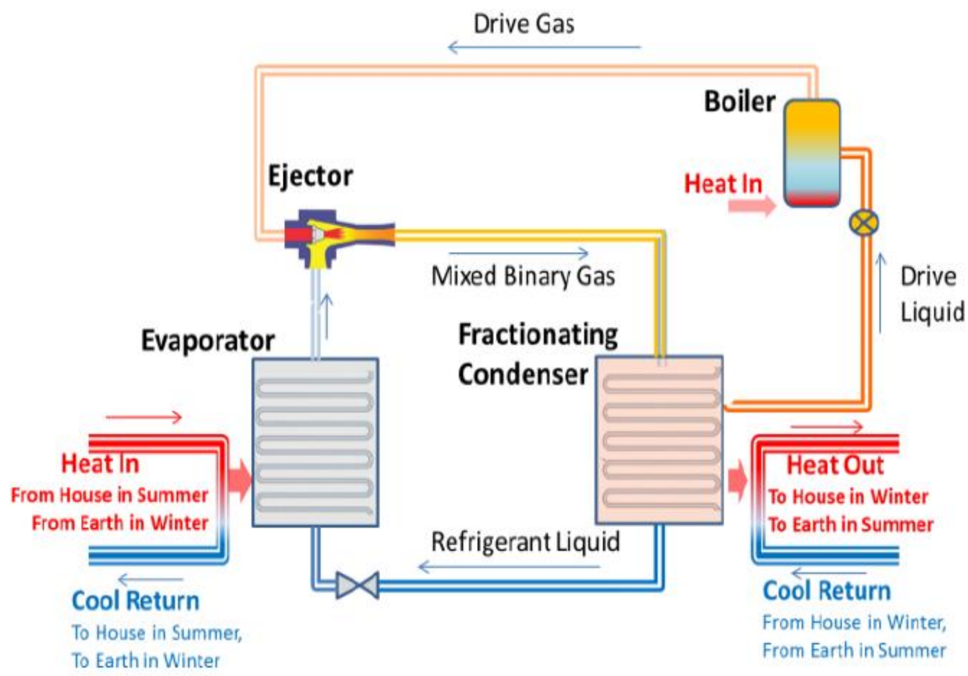

Figure 29: Binary fluid ejector heat pump system

Source: Glanville (2014)[149]

Technical Maturity and Current Developmental Status

Ejectors are currently available as a component for a variety of automotive, refrigeration, and industrial applications, but are in the development stage for commercial HVAC applications. Research by CANMET, Gas Technology Institute (GTI), and other organizations is underway on several ejector heat pump concepts for industrial drying, air-source heat pump, and ground-source heat pump applications.[150,151]

Barriers to Market Adoption

Beyond continued product development and commercialization, the major challenge for ejector heat pumps will be cost-effectiveness relative to conventional technologies.

Energy Savings Potential

Potential Market and Replacement Applications

Ejector heat pumps could be viable replacements for most commercial HVAC systems, particularly gas-fired space heating systems.

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[149] Glanville, Paul. 2014. "Industrial Heat Pumps in Agricultural Drying Applications." GTI. International Gas Union Research Conference. September 2014. Available at: http://members.igu.org/old/IGU%20Events/igrc/igrc-2014/presentations/to6-3_glanville_draft.pdf

[150] CanmetENERGY. 2015. "Capturing the Value of Thermal Energy - Innovations in Ejector Technology from CanmetENERGY." Natural Resources Canada. 2015. Available at: http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/energy/pdf/brochure-ejecteurs_EN.pdf

[151] Kooy, Rich. 2016. "Thermally-Driven Ground-Source Heat Pump." Utilization Technology Development. Research Project Summaries. 2015-2016 Project No. 1.14.G. Summary Report. Available at: https://www.utd-co.org/Documents/UTD-Annual-Report-Project-Summaries-2015-2016.pdf

Energy Savings

Past studies have shown that ejector heat pumps historically were only able to achieve cooling COPs of 0.2-0.4 and heating COPs of 1.1-1.3.[152] These performance levels would limit the potential for primary energy savings, especially for space cooling, relative to more conventional HVAC systems. The recent developments in binary fluid ejector technology have raised the prospect of ejector heat pumps for commercial HVAC energy savings.

Modeling research and laboratory testing by May-Ruben Thermal Solutions and partners suggests that the binary fluid ejector system could achieve COPs of 2.0 for space heating and 1.0 for space cooling, when coupled with a ground-loop heat exchanger.[153] If realized, this performance breakthrough could provide up to 60% energy savings over conventional gas-fired heating systems. Primary energy consumption for space cooling would be comparable to existing systems. Continued research is necessary to optimize the fluid pairs, nozzle design, and other components for each application.

Cost and Complexity

The cost of the next generation of ejector heat pumps is unknown, given its early development stage. The systems may require larger equipment sizes to accommodate the specialized heat exchangers, and they may involve higher installation complexity, especially if a ground-loop heat exchanger is required.

Peak-Demand Reduction and Other Non-Energy Benefits

The gas-fired ejector technology could provide significant peak demand reduction for space cooling, if the parasitic energy consumption of the pumps, fans, etc. is reasonable. Depending on the specific binary fluid pairs, the technology could utilize low-GWP or no-GWP working fluids.

Next Steps for Technology Development

Gas-fired ejector heat pumps show promising energy savings potential if real-world performance can match modelled estimates. Continued R&D is necessary to identify optimal working fluid pairs, nozzle designs, and other system configurations for various commercial HVAC applications.

Table 30 presents the potential next steps to advance ejector heat pumps.

Table 30: Recommended Next Steps for the Development of Ejector Heat Pumps

Activities
Continue to investigate the potential for binary fluids ejectors to achieve high efficiency performance in various applications
Develop prototype ejector heat pumps for heating-dominated markets and conduct field testing

[152] Rahamathullah et al. 2013. "A Review of Historical and Present Developments in Ejector Systems." International Journal of Engineering Research and Applications. Vol. 3, Issue 2, March-April 2013.
[153] Kooy, Rich. 2016. "Thermally-Driven Ground-Source Heat Pump." Utilization Technology Development. Research Project Summaries. 2015-2016 Project No. 1.14.G. Summary Report. Available at: https://www.utd-co.org/Documents/UTD-Annual-Report-Project-Summaries-2015-2016.pdf

6.3 Fuel Cell Combined Cooling, Heating, and Power System

Brief Description	The packaged system provides both space cooling and electric power to buildings by utilizing the waste heat from a natural gas fuel cell to operate an evaporative liquid-desiccant cooling cycle.

Technology Characteristics	Value	Comments
Technology Category	Alternative Gas-Fired Heat Pump Technologies	
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)	Laboratory testing of initial prototypes completed, preparing for field demonstrations
Unit Energy Savings	50%	Projected 50% primary energy savings for space cooling, but building level savings are higher due to on-site electricity generation
Technical Energy Savings Potential	655 TBtu	Commercial RTU space cooling
Non-Energy Benefits	1-2 quantified benefits	Low-GWP working fluids for reduced direct GHG emissions and potential for noise reduction, IAQ improvement from increased outside air supply to building, comfort improvement through sensible/latent control
Peak Demand Reduction Potential	High	Natural gas fuel cell generates electricity to power both A/C system and other building loads
Relative Cost Premium	High	Estimated cost of $45,000 for 5-ton RTU product, which is substantially higher than conventional RTUs, but this does not factor in savings due to electricity generation
Operational Complexity	High	Incorporates advanced membrane and liquid desiccant systems in addition to a fuel cell generation system

Background

Technology Description

Commercial buildings using conventional RTUs experience both high annual electricity consumption and electrical demand due to the electrically driven vapor-compression HVAC systems. BePowerTech has developed a combined electrical generation and HVAC system that achieves energy and cost savings using advanced cooling technologies and natural gas as the primary energy source. The technology uses the waste heat from a natural gas fuel cell to drive an evaporative-liquid desiccant A/C cycle, which substantially reduces the electricity consumption for space cooling while also generating electricity for other uses in the building. The technology improves on current combined-heat-and-power (CHP) systems by incorporating every component into a packaged RTU system and featuring the evaporative liquid-desiccant cooling system. Figure 30 provides a simplified diagram of the system operations:

- The fuel cell operates continuously to provide both electricity and waste heat, with a higher heating value (HHV) electrical efficiency in the mid-40% range. The electricity powers building loads and offsets the grid-supplied electricity demand throughout the day.

- When the building calls for space cooling, the waste heat and condensed water from the fuel cell provide the primary inputs for the multi-stage A/C process using both a liquid-desiccant dehumidifier and indirect/direct evaporative cooler.
- Warm, humid process air (a combination of outside and return air) first enters the dehumidifier, where the process air stream flows through a heat and mass exchanger (HMX) containing a series of plates. The air is separated from lithium chloride (LiCl) liquid desiccant by a selectively permeable membrane (HMX2) that allows the liquid desiccant to absorb water vapor from the process air without direct contact between the two streams. This transfer warms the process air. LiCl desiccant is regenerated for reuse using waste heat from the fuel cell (HMX1).
- The warm, dry process air then enters another set of plates (HMX3) that uses water recovered from the fuel cell to provide sensible cooling to the supply air stream through an indirect evaporative cooling process. A portion of the dehumidified air is separated and routed across a water channel, evaporates the water in that channel, and cools. This cool air stream then absorbs heat from the process air across a heat exchanger. The cool, dry air stream then enters the building.

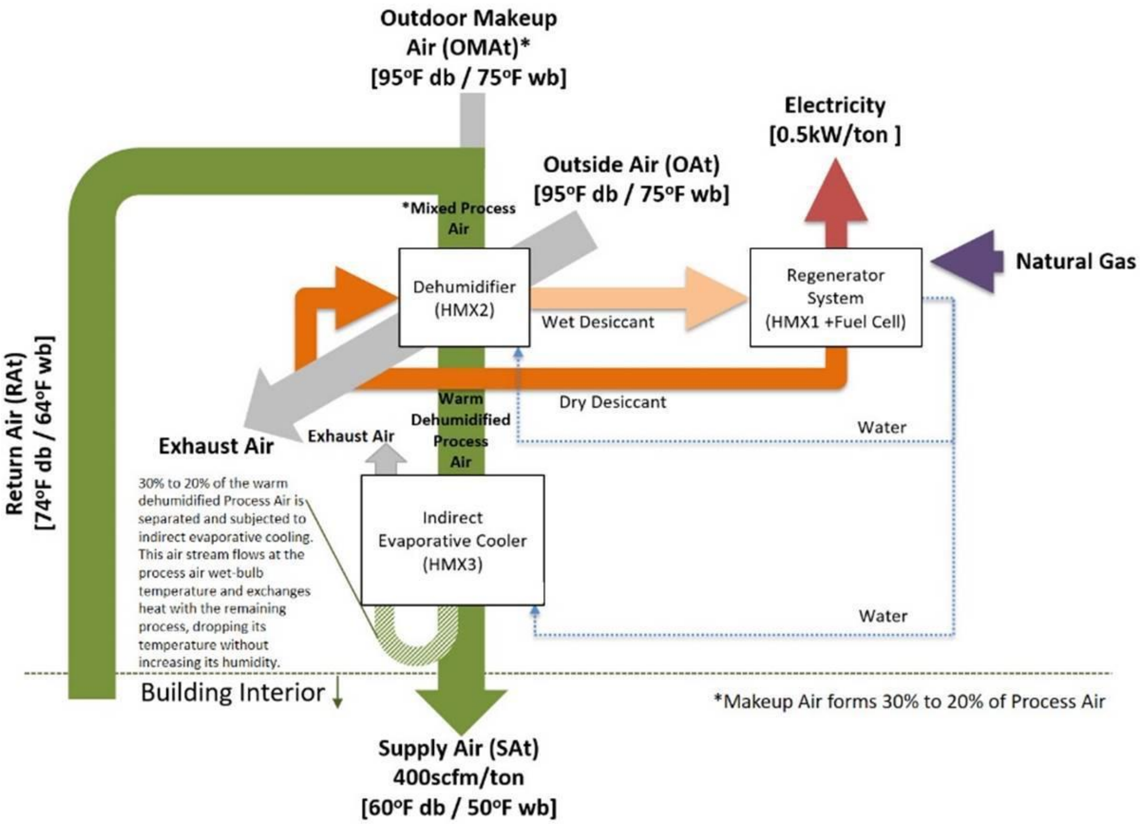

Figure 30: Process diagram of fuel cell combined cooling, heating, and power system

Source: BePowerTech (2017)[154]

Figure 31 provides an illustration of the RTU product envisioned by BePowerTech. The current benchtop demonstration unit (5 tons cooling, 5 kW electric) was tested at ORNL in 2015-2016 and showed promising

[154] Betts et al. 2017. "Oak Ridge National Laboratory Small Business Voucher CRADA Report: Natural Gas Powered HVAC System for Commercial and Residential Buildings." ORNL. April 2017. Available at: http://info.ornl.gov/sites/publications/files/Pub74419.pdf

performance and efficiency.[155] The natural gas fuel cell is designed to operate continuously to generate electricity for on-site use and to provide inexpensive heating for the desiccant-enhanced evaporative (DEVAP) A/C system, the latter which was originally developed by NREL.[156] Annual economic savings were estimated to be $5,000-$10,000, assuming 10 MWh A/C offset by the DEVAP cycle, 5,000 therm/yr. gas consumption, and 43 MWh/yr. electricity production.[157]

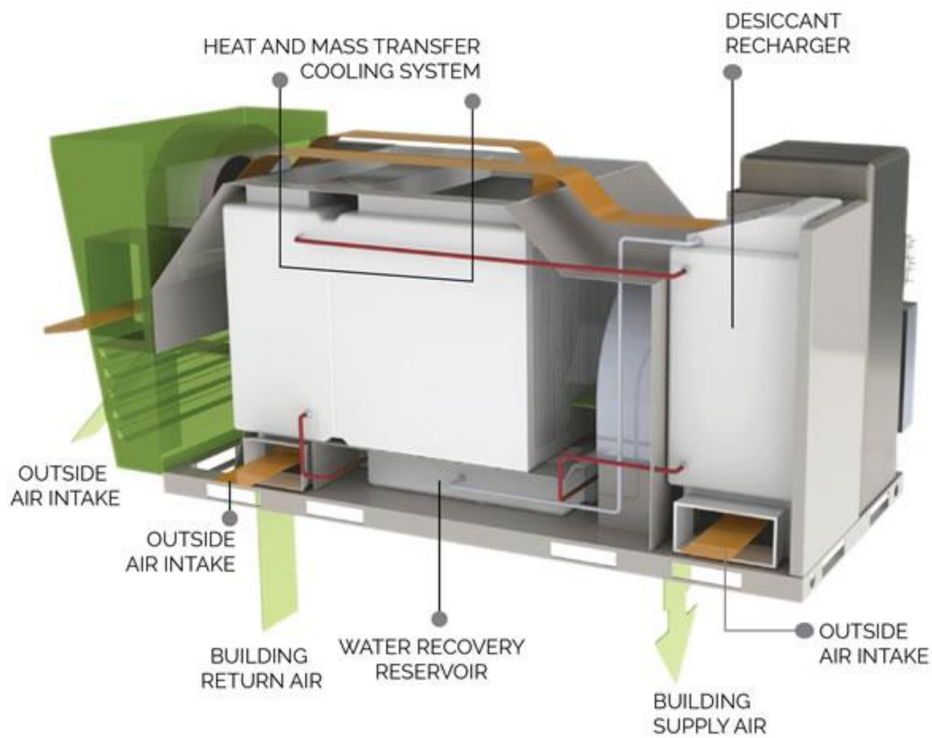

Figure 31: Illustration of BePowerTech RTU product

Source: BePowerTech (2017)[158]

Technical Maturity and Current Developmental Status

BePowerTech has conducted laboratory testing at ORNL and is in the process of preparing next-generation prototypes for field testing with utility partners.[159] The individual system components (e.g., fuel cell, evaporative cooler, liquid desiccant dehumidifier) are commercially available individually, but the combined package RTU is still under development.

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155 Betts et al. 2017. "Oak Ridge National Laboratory Small Business Voucher CRADA Report: Natural Gas Powered HVAC System for Commercial and Residential Buildings." ORNL. April 2017. Available at: http://info.ornl.gov/sites/publications/files/Pub74419.pdf

156 NREL. 2012. "NREL's Energy-Saving Technology for Air Conditioning Cuts Peak Power Loads Without Using Harmful Refrigerants." July 2012. Available at: http://www.nrel.gov/docs/fy12osti/55740.pdf

157 Betts et al. 2017. "Oak Ridge National Laboratory Small Business Voucher CRADA Report: Natural Gas Powered HVAC System for Commercial and Residential Buildings." ORNL. April 2017. Available at: http://info.ornl.gov/sites/publications/files/Pub74419.pdf

158 BePowerTech. Accessed August 2017. Available at: https://www.bepowertech.com/technology.php

159 Benold, Laura. 2016. "Be Power Tech Air Conditioners Generate Electricity, Empower Building Owners." Smart Cities Connect Media & Research. December 2016. Available at: http://smartcitiesconnect.org/be-power-tech-air-conditioners-generate-electricity-empower-building-owners/

Barriers to Market Adoption

Beyond technology development, the largest barriers to a fuel cell combined cooling, heating, and power system are cost and complexity, which are discussed further below. Building owners, HVAC designers, and service technicians would also require specialized training enabling them to operate, design, install, and maintain both the fuel cell and DEVAP cooling systems. In addition, electricians are required to properly connect the fuel cell system to the building's electrical panel.

Energy Savings Potential

Potential Market and Replacement Applications

The technology could replace most packaged RTU systems for space cooling, dehumidification, and potentially space heating applications. The researchers claim the technology can provide space heating using the recovered waste heat from the fuel cell, but performance testing to date has only validated the space cooling and electricity generation components.

Energy Savings

Evaluating the HVAC energy savings for this technology is difficult because the space cooling benefit is a byproduct of the fuel cell's electricity generation. The fuel cell is designed to operate continuously (year-round), creating both electricity for the building and heat to recharge the liquid desiccant, but the space cooling system only operates when necessary (e.g., summer). As noted previously, the entire system substantially reduces grid-supplied electricity consumption (10 MWh/yr. offset + 43 MWh/yr. production) and increases natural gas consumption (5,000 therm/yr.). Using previous estimates for the DEVAP A/C system (25-81% depending on climate), we estimate 50% primary energy savings of 50% for space cooling.[160]

Cost and Complexity

The BePowerTech technology is designed to replace packaged RTUs, which is a mature product category with many competitors offering cost-effective and reliable equipment of various capacities. BePowerTech estimates the cost for the 5-ton system would be $45,000 or $13,000/yr. leased.[161] While the combined HVAC and electricity cost savings can result in reasonable payback periods (2-5 years)[162], the high incremental cost may be prohibitive for some building owners. Leased commercial buildings may pose an issue due to split-incentives where the owner pays for the RTUs, and the tenant pays for the utility bills. In addition, interconnection and net metering rules for small non-renewable generating systems varies substantially among utilities and states.

Peak-Demand Reduction and Other Non-Energy Benefits

By incorporating a heat activated cooling system and on-site electrical generator, the fuel cell combined cooling and power system would substantially lower the annual and peak demand for commercial buildings. The DEVAP A/C system uses working fluids with zero GWP, and the system could also improve occupant comfort by reducing outside noise and increased outside air supply to building.

Next Steps for Technology Development

The fuel cell combined cooling and power system is a promising technology for commercial buildings due to its energy efficiency, peak demand, and distribution generation attributes. The greatest challenges will be to

[160] NREL. 2012. "NREL's Energy-Saving Technology for Air Conditioning Cuts Peak Power Loads Without Using Harmful Refrigerants." July 2012. Available at: http://www.nrel.gov/docs/fy12osti/55740.pdf

[161] Betts, Daniel. 2015. "Electricity Producing Air Conditioning Systems." BePowerTech. 2015. Available at: https://www.nrel.gov/workingwithus/assets/pdfs/2015-igf-be-power-tech.pdf

[162] Tilghman, Matt. 2016. "Electricity Producing Air Conditioning Systems." ASHRAE Winter Conference. July 2016. Available at: https://www.bepowertech.com/technology.php#technical2

develop and demonstrate a cost-effective product that could replace the reliable and ubiquitous packaged RTU using the vapor-compression cycle.

Table 31 presents the potential next steps to advance fuel cell combined cooling, heating, and power systems.

Table 31: Recommended Next Steps for the Development of Fuel Cell Combined Cooling, Heating, and Power System

Activities
Continue development of integrated prototypes for laboratory and field testing
Conduct field demonstrations with utility partners to capture energy efficiency, peak demand, and distributed generation benefits
Develop modelling tools for HVAC engineers to quickly identify opportunities for the technology based on customer information on building type, current utility consumption, climate, etc.

7 Alternative System Architectures

Alternative System Architectures provide localized comfort to building occupants to reduce the operating requirements of traditional HVAC systems. Table 32 provides a brief description, and the final ranking, of the high priority technology options in the Alternative System Architectures category.

Commercial HVAC systems provide thermal comfort to building occupants by controlling the temperature of the indoor space. Traditionally, a single thermostat and its set point schedule govern the temperature in each zone, which can create uncomfortable conditions for occupants for several reasons.

- Different areas of a building or floor typically receive different amounts of space conditioning and airflow because of the HVAC system design and building layout.
- People tend to prefer different temperature and airflow conditions, owing to their clothing, metabolism, and personal preferences.
- In addition, the HVAC system works to maintain the set point temperature throughout the entire space, even during low occupancy periods.

When building occupants are uncomfortable because of an overly aggressive temperature set point, whether too cold or too warm, or the HVAC system operates during extended periods of low occupancy, there is room for improved energy efficiency and productivity.

Table 32: Brief Descriptions for Alternative System Architectures

Technology	Brief Description	Technical Maturity	Technical Energy Savings Potential (Quads/yr.)	Final Ranking
Robotic Personal Comfort Device (7.1)	A miniaturized heat pump on a motorized base that provides localized space heating and cooling for building occupants as they travel around the building.	Technology Demonstration (TRL 5-6)	0.53	3.80
Dynamic Clothing Technologies for Personal Comfort (7.2)	Advanced materials and fabrics that reject or trap heat more efficiently than other materials, so that building occupants require less thermal comfort from the HVAC system.	Technology Development (TRL 3-4)	0.53	3.40
Wearable Devices for Personal Comfort (7.3)	Wearable devices, furniture, and other innovations that provide personalized comfort to building occupants, using small-scale heating and cooling elements.	Technology Demonstration (TRL 5-6)	0.35	2.60

7.1 Robotic Personal Comfort Device

Brief Description	A miniaturized heat pump on a motorized base that provides localized space heating and cooling for building occupants as they travel around the building.

Technology Characteristics	Value	Comments
Technology Category	Alternative System Architectures	
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)	Products are under development and testing at UMD and Mobile Comfort Inc.
Unit Energy Savings	15%	Estimated savings range from 12-31%, based on equipment energy consumption and the temperature setback of the main building thermostat
Technical Energy Savings Potential	558.7 TBtu	Total commercial HVAC energy consumption
Non-Energy Benefits	Potential for significant benefits, but not well documented	The technology would provide individualized comfort to building occupants
Peak Demand Reduction Potential	High	Substantial reduction, as the robots would charge during off-peak hours to provide cooling during peak hours
Relative Cost Premium	Significantly higher cost	Could allow conventional system downsizing, but with each occupant requiring a robot and its associated charging needs, cost would be higher
Operational Complexity	Moderately higher complexity	Requires robotic logistics and charging systems, in addition to a conventional HVAC system

Background

Technology Description

Researchers at UMD have developed a robotic personal comfort device that can provided localized space heating and cooling to an individual as they travel throughout an indoor space. The "RoCo" or Roving Comforter consists of a miniaturized heat pump operating on a battery-powered, motorized base that connects with a user's phone to get their location information.[163] Figure 32 shows the RoCo without its housing, exposing key components. RoCo incorporates a suite of sensors to intelligently avoid obstacles and gently

[163] Fears, Darryl. 2016. "This Robot Follows You Around and Blasts You with Air Conditioning." The Washington Post. June 2016. Available at: https://www.washingtonpost.com/news/energy-environment/wp/2016/06/30/this-robot-is-really-cool-seriously-its-a-rolling-air-conditioner/?utm_term=.b459543cd111

direct airflow to the person. It uses a phase change material (PCM) thermal storage chamber for improved energy efficiency.

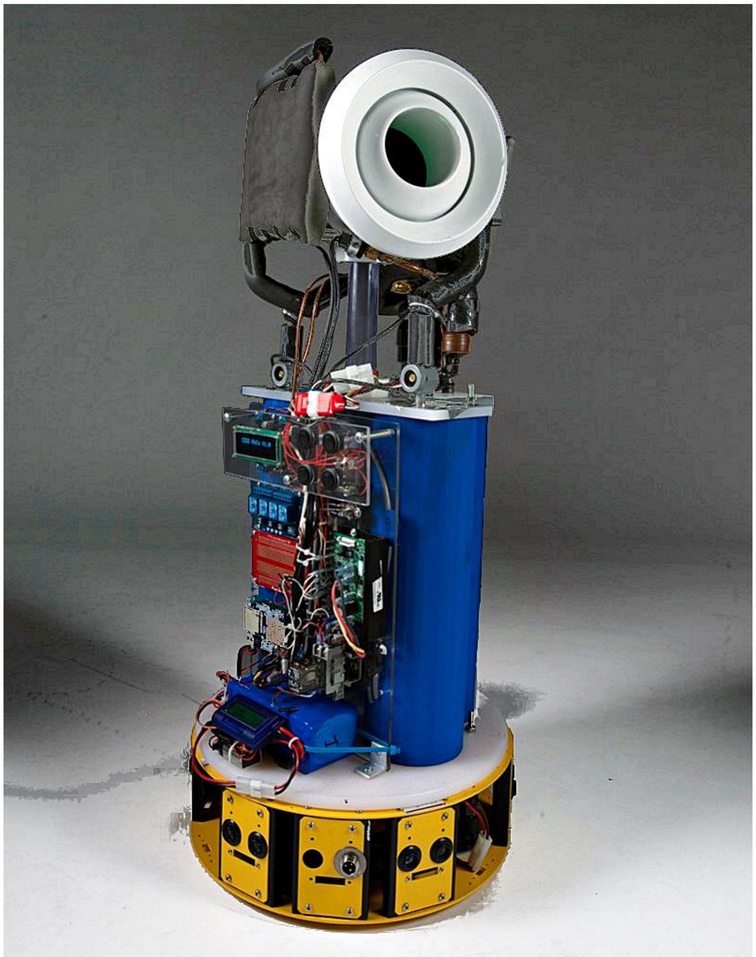

Figure 32: RoCo roving comforter

Source: UMD (2017)[164]

Personalized comfort technologies could provide energy savings by allowing the traditional building HVAC system to expand its temperature set points (e.g., from 72°F to 77°F). Because the robotic device consumes electricity itself, the actual energy savings will depend on the energy efficiency of the RoCo system, as well as its battery charger. UMD currently projects the ~100W devices could achieve cooling COPs of 2.0-3.0 and heating COPs of 2.0-2.5, with the ability to provide comfort for several hours per charge.[165] In addition, the technology could provide substantial peak demand savings if charged during off-peak hours. Beyond energy savings, the technology can have significant benefits for outdoor or semi-conditioned applications such as warehouse and factory facilities where heating and cooling of large spaces has traditionally been impractical.[166]

[164] UMD. 2016. "Roving Comforter (RoCo) – A Personal Cooling and Heating Device." Accessed August 2017. Available at: http://www.ceee.umd.edu/roco
[165] UMD. 2015. "Robotic Personal Conditioning Device." 2015 ARPA-e Innovation Summit. Available at: https://arpa-e.energy.gov/sites/default/files/05_UMD_Roco_DELTA.pdf
[166] Mobile Comfort Inc. Website. Accessed August 2017. Available at: http://www.mobilecomfort.us/about-us.html

Technical Maturity and Current Developmental Status

UMD researchers are developing the technology as part of the ARPA-e's Delivering Local Thermal Amenities (DELTA) program.[167] The start-up company Mobile Comfort Inc. plans to commercialize the product and is in discussions with several manufacturing partners.[168] The researchers have created several generations of the RoCo product, and are continuing to advance the efficiency and cost-effectiveness of the technology.

Barriers to Market Adoption

The major barriers to robotic personal conditioning devices are upfront cost, space requirements for charging and storage, connectivity with traditional building controls, and the required operational changes within buildings. The technology could readily operate in semi-conditioned buildings, such as warehouses, to provide localized cooling where no traditional cooling system exists. In these situations, personal comfort and productivity would improve, but building energy consumption would increase. Logistics challenges can arise in more traditional commercial HVAC environments. For example, a space-constrained office or service building may not have sufficient floor space to accommodate robots for each individual.

Energy Savings Potential

Potential Market and Replacement Applications

While practical challenges do exist, the robotic personal conditioning devices could potentially affect most commercial buildings by allowing more efficient temperature setpoints for the traditional HVAC system.

Energy Savings

UMD projects that robotic personal conditioning devices could provide 12-31% HVAC energy savings by adjusting temperature setpoints by 4-6 °F, depending on climate region and other factors.[169,170] These initial estimates are based on building energy modelling, rather than demonstrated performance in laboratory or field environments. We conservatively estimate 15% technical energy savings for both space heating and space cooling based on these initial energy savings estimates, as well as the understanding that the technology will be used in applications where HVAC systems do not currently operate.

Cost and Complexity

Researchers project the cost of each device could be on the order of $50-$150, once fully developed. The technology could theoretically allow for HVAC equipment downsizing, but this would be a long-term goal once the performance, energy efficiency, reliability, and other key attributes are proven out. As noted previously, the devices increase the complexity of building operations by requiring space for battery charging and storage, as well as the logistics of robots following occupants throughout the space.

Peak-Demand Reduction and Other Non-Energy Benefits

Robotic personal conditioning devices could increase the peak-demand reduction of buildings by allowing temperature setpoints to be relaxed during peak hours, if the robots' batteries can be charged during off-peak times. The technology provides a form of energy storage by satisfying peak thermal loads with time-delayed grid power consumption.

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[167] ARPA-e. 2014. "Robotic Personal Conditioning Device." December 2014. Available at: https://arpa-e.energy.gov/?q=slick-sheet-project/robotic-personal-conditioning-device

[168] Mobile Comfort Inc. Website. Accessed August 2017. Available at: http://www.mobilecomfort.us/about-us.html

[169] Mallow and Gluesenkamp. 2017. "Personal Cooling and the Roving Comforter." Heat Pumping Technologies Magazine. Volume 35, No. 2. Available at: http://web.ornl.gov/sci/usnt/news_letters/HPTMagazineNo22017.pdf

[170] UMD. 2016. "Roving Comforter (RoCo) – A Personal Cooling and Heating Device." 2016 ARPA-e Innovation Summit. Available at: http://www.arpae-summit.com/paperclip/exhibitor_docs/16AE/University_of_Maryland_CEEE_1011.pdf

Next Steps for Technology Development

Robotic personal conditioning devices incorporating energy efficient heat pumps are a promising technology that could change the way buildings maintain comfortable indoor environments. Prototype development has proven the technical feasibility of the technology, but additional work is necessary to improve the performance, cost, aesthetics, and usability of the products. In addition, laboratory and field research will help quantify the comfort and energy savings benefits of the product, and inform developers regarding how the technology should integrate with traditional HVAC control systems and other building functions.

Table 33 lists potential next steps to advance robotic personal comfort devices.

Table 33: Recommended Next Steps for the Development of Robotic Personal Comfort Devices

Activities
Continue to develop prototypes to improve the performance, cost, aesthetics, and usability of products
Conduct laboratory research on personal comfort preferences with the robotic devices
Conduct field studies in relevant environments to understand occupant preferences, energy savings potential, and operational requirements

7.2 Dynamic Clothing Technologies for Personal Comfort

Brief Description	Advanced materials and fabrics that reject or trap heat more efficiently than other materials, so that building occupants require less thermal comfort from the HVAC system.

Technology Characteristics	Value	Comments
Technology Category	Alternative System Architectures	
Technology Readiness Level (TRL)	Early Stage Research (TRL 1-2)	Initial concept and material development
Unit Energy Savings	15%	Estimated savings from adjusting the temperature setpoints to more efficient settings; assumes no additional localized power consumption
Technical Energy Savings Potential	558.7 TBtu	All commercial HVAC energy consumption
Non-Energy Benefits	Potential for significant benefits, but not well documented	The technology would provide individualized comfort to building occupants
Peak Demand Reduction Potential	Low	Peak-demand reduction would be as expected for the average level of energy savings, unless coordinated with the building HVAC system during DR events
Relative Cost Premium	Moderately higher upfront cost	Researchers project that the fabric technologies would contribute to modest cost increases for users, but a building-level system would require significant investment in new clothing
Operational Complexity	Moderately higher complexity	Adjusting the thermostat setpoints is simple, but maintaining compliance for all building occupants may prove challenging unless a uniform is required for employment

Background

Technology Description

Several researchers have developed advanced materials and fabrics that could potentially allow building operators to adjust the temperature setpoints to more efficient settings (e.g., from 72 °F to 76 °F in summer) while still maintaining personal comfort. The specialized materials either reject or trap heat more efficiently than other natural or synthetic materials, so that building occupants feel warmer or cooler and require less thermal comfort from the HVAC system. With more adaptable clothing, occupants will feel comfortable even if the thermostat is set at "relaxed" temperature setting (i.e., higher in summer, lower in winter), which would reduce HVAC energy consumption. To offset the use of conventional HVAC systems, the majority of building occupants would need to wear clothing using these products.

Table 34 highlights several of the concepts under development as part of the ARPA-e Delivering Efficient Local Thermal Amenities (DELTA) program[171] and other research efforts. The general principle of these technologies is to trap body heat when ambient temperatures are low and reject body heat when temperatures are high. Some concepts blend polymers into the textile fibers such that fiber thickness and pore opening adjust with temperature. Other concepts use specialized materials that change the amount of thermal radiation (i.e., body heat) that transfers from the skin surface through the material. Each of these concepts is intended to integrate with conventional clothing fabrics and operate without user intervention.

Table 34: Examples of Dynamic Clothing Technologies for Personal Comfort

Research Organization	Technology Name	Brief Description
Otherlab	Passive Thermo-Adaptive Textiles	Developing fabrics with polymer biomorph materials that change their physical shape in response to ambient temperatures, thus adjusting the insulating properties of the material.[172]
Stanford University	Photonic Structure Textiles	Developing photonic-structured fabrics that maintain personal comfort by adjusting how the fabric interacts with body's thermal radiation. The textiles will offer high transmissivity of body heat when cooling is needed, or high reflectance of body heat for heating.[173]
University of California (UC) Irvine	Thermocomfort Cloth	Developing a fabric that dynamically changes its thermal emission properties to regulate body temperatures, using adaptive materials inspired by squid skin[174]
UC San Diego	Adaptive Textile Technology	Developing a specialized fabric that adjusts its thickness and pore size to modulate ventilation and insulation properties with ambient temperature. Use embedded thermoelectric devices to maintain skin temperature of 93F.[175] Note: The embedded thermoelectrics within the fabric would be similar to Wearable Devices for Personal Comfort (Section 7.3).
UMD	Meta-Cooling Textile	Developing a fabric using thermoresponsive polymers that changes the microstructure of the fabric. The pore size increases for greater ventilation during warm weather and restricts pore size during cold weather to increase insulation[176]
MIT	Hybrid Optical-Thermal Materials	Development of specialized materials that combine optical and thermal management properties to create fabrics that are opaque to visible light, but highly transparent in the infrared range. This would allow a user to efficiently shed heat through thermal emission while wearing the fabric.[177]

[171] ARPA-e. 2014. "ARPA-e DELTA Program." December 2014. Available at: https://arpa-e.energy.gov/?q=arpa-e-programs/delta
[172] Ridley et al. 2015. "Passive Thermo-Adaptive Textiles With Laminated Polymer Bimorphs." Otherlab. ARPA-e DELTA Program Kickoff. May 2015. Available at: https://arpa-e.energy.gov/sites/default/files/04_Otherlab_DELTA_Kickoff.pdf
[173] Shanhui and Cui. 2016. "Photonic Structure Textiles for Localized Thermal Management." Stanford University. ARPA-e Innovation Summit. January 2016. Available at: http://www.arpae-summit.com/paperclip/exhibitor_docs/16AE/Stanford_University_661.pdf
[174] Gorodetsky, Alon. 2015. "Project Title: Thermocomfort Cloth Inspired by Squid Skin." UC Irvine. ARPA-e DELTA Program Kickoff. May 2015. Available at: https://arpa-e.energy.gov/sites/default/files/09_UCI_DELTA_Kickoff.pdf
[175] Labios, Liezel. 2015. "Engineers Win Grant to Make Smart Clothes for Personalized Cooling and Heating." UC San Diego. June 2015. Available at: http://jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=1753
[176] Wang, YuHuang. 2015. "Meta-Cooling Textile." UMD. ARPA-e DELTA Program Kickoff. May 2015. Available at: https://arpa-e.energy.gov/sites/default/files/14_UMD_Wang_DELTA_kickoff2015.pdf
[177] Boriskina et al. 2015. "Hybrid Optical-Thermal Devices and Materials for Light Manipulation and Radiative Cooling." MIT. September 2019. Available at: https://dspace.mit.edu/handle/1721.1/108170#files-area

Technical Maturity and Current Developmental Status

Each of these dynamic clothing technologies is in the early stage of R&D. Most of the ARPA-e DELTA projects are awarded through 2018-2019, but several have already partnered with major clothing companies.

Barriers to Market Adoption

The largest barrier to market adoption will be the requirement to have virtually all building occupants wearing clothing that incorporates these technologies. Clothing options using the technologies may not be available in the size or style needed for all building occupants. Even in buildings where the majority of workers use a uniform, outside parties such as customers, clients, or other visitors may be uncomfortable in the less-controlled environment.

Energy Savings Potential

Potential Market and Replacement Applications

If dynamic clothing products are successfully developed and deployed, resulting thermostat adjustments could provide energy savings for commercial HVAC applications.

Energy Savings

The energy savings benefits of dynamic clothing technologies have not been demonstrated in full-scale laboratory or field testing to date. Nevertheless, research on the overall concept of maintaining comfort at relaxed thermostat settings has shown that adjusting temperature setpoints by 4 °F could achieve energy savings of 15% and greater.[178] In addition, the majority of the clothing technology concepts are passive, not requiring ancillary electricity consumption like other personalized cooling concepts (Section 7.1 and 7.3).

Cost and Complexity

The incremental cost of dynamic clothing technologies is unknown, but researchers do not project a high cost for the fabrics. High-performance clothing for athletics and other activities can carry a price premium, which be a target market for initial introduction of dynamic clothing technologies. As noted previously, occupants in an entire building or HVAC zone would need to have clothing that features the technology or else the higher or lower indoor temperatures may cause discomfort to non-participants.

Peak-Demand Reduction and Other Non-Energy Benefits

Peak-demand reduction would be as expected for the average level of energy savings, unless it is coordinated with a building HVAC system during DR events. The dynamic clothing technology could improve comfort to building occupants but, being passive technology, it would not provide much ability for personalization.

Next Steps for Technology Development

Enhancing traditional clothing fabrics with embedded technologies that change their thermal properties could provide substantial energy savings, but there are several practical issues. A building would need to achieve near-100% occupant compliance, and the available clothes would need to satisfy every size and style. While these issues may inhibit widespread adoption, dynamic clothing technologies may find attractive markets in a variety of smaller, more specific applications where current fabrics provide imperfect comfort.

Table 35 list potential next steps to advance dynamic clothing technologies for personal comfort.

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[178] ARPA-e. 2015. "DELTA Program Overview." May 2015. Available at: https://arpa-e.energy.gov/sites/default/files/documents/files/DELTA_ProgramOverview.pdf

Table 35: Recommended Next Steps for the Development of Dynamic Clothing Technologies for Personal Comfort

Activities
Continue to develop fabrics incorporating different dynamic clothing technology concepts
Develop full-scale prototypes for use in laboratory comfort testing with manikins and human participants
Conduct testing on several human participants in a simulated office or other commercial environment to understand the product's comfort and energy savings potential

7.3 Wearable Devices for Personal Comfort

Brief Description	Wearable devices, furniture, and other innovations that provide personalized comfort to building occupants, using small-scale heating and cooling elements.

Technology Characteristics	Value	Comments
Technology Category	Alternative System Architectures	
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)	Prototypes and early products are available, but field testing for energy savings is underway
Unit Energy Savings	10%	Overall energy savings from adjusting temperature setpoints for main HVAC system; savings are slightly offset by device charging requirements
Technical Energy Savings Potential	330.2 TBtu	All commercial HVAC systems
Non-Energy Benefits	Potential for significant benefits, but not well documented	The technology would provide individualized comfort to building occupants; potential peak-demand reduction during DR events
Peak Demand Reduction Potential	Medium	For technologies that use batteries, the grid-tied electricity demand could decrease during peak events, in favor of increased cooling from battery-powered devices
Relative Cost Premium	Significantly higher cost	Limited research exists about the tradeoff between personal comfort devices and downsized central HVAC systems, but buildings would require wearable devices for every building occupant
Operational Complexity	Moderately higher complexity	Having users wear devices, or have an additional device at their workstation, could be managed, but it does require more separate physical elements than a centralized HVAC system.

Background

Technology Description

Providing small amounts of cooling or heating to certain parts of the body can have a disproportionate impact on a person's overall comfort. For example, providing cooling to the underside of the wrist, bottom of the foot, forehead, torso, or neck can create a whole-body cooling sensation, without thermally conditioning every area. Several researchers and product vendors are developing wearable devices, undergarments, and furniture that can provide personalized comfort to a user through small-scale heating and cooling elements. When used in commercial buildings, these devices could allow thermostat set points to be extended to more efficient temperatures (i.e., higher in the summer, lower in the winter) while maintaining occupant comfort.

Figure 33 highlights two personal comfort system concepts. The MIT start-up Embr Labs is developing a bracelet that uses embedded thermoelectric devices to provide localized heating and cooling to users' wrists for indoor and outdoor comfort.[179,180] Researchers at the UC Berkeley have developed and tested specialized office chairs that have small heating strips (14W) and fans (4W) embedded in the chair seat and back that allow users to control the amount of localized heating and cooling.[181,182] The start-up Personal Comfort Systems is commercializing the technology under the name Hyperchair. [183] Other vendors also offer similar products that use thermoelectrics for office chairs,[184] automotive seats,[185] and mattresses.[186] Researchers at Cornell University are developing a personal conditioning system that uses a small, detachable thermoelectric device to blow warm or cool air through a series of microscale tubes embedded in an undershirt.[187,188]

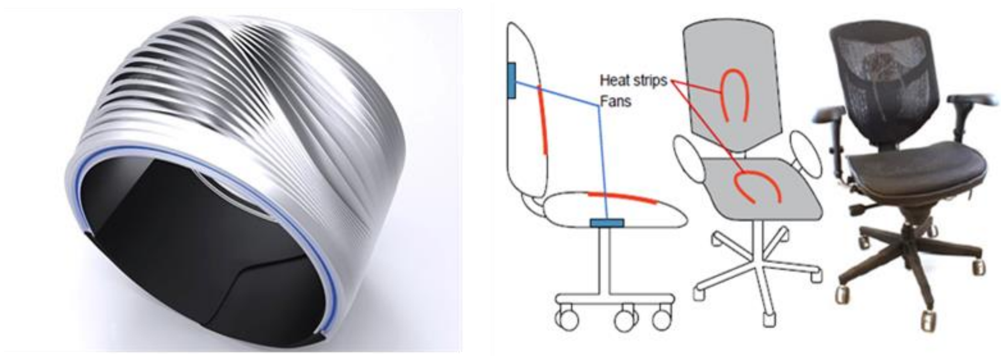

Figure 33: Example wearable devices for personal comfort

Source: Chiu (2016) [left], Andersen et al. (2016) [right]

Personal comfort systems provide sensible thermal conditioning to supplement conventional HVAC systems, rather than replace them completely. The products could provide energy savings by satisfying localized comfort requirements using less energy than the building's HVAC system. In this way, the central HVAC system could maintain a more moderate temperature schedule as a baseline and allow individual occupants to tailor their comfort using their individual devices. This strategy could provide energy savings for commercial buildings as a supplemental system, but is not anticipated to reduce the capacity of conventional HVAC systems. In addition, the devices could provide occupant feedback to adjust the centralized HVAC system setpoints. For example, if most occupants are using the personal heaters in the summer to keep comfortable,

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179 EMBR Labs Website. Accessed August 2017. Available at: http://www.embrlabs.com/

180 Chiu, Yu-Tzu. 2016. "Wristify: Thermoelectric Wearable Would Reduce Energy Consumption." IEEE Spectrum. June 7, 2016. Available at: http://spectrum.ieee.org/energywise/energy/environment/wristify-thermoelectric-bracelet-would-reduce-energy-consumption

181 Hoban, Virgie. 2013. "UC Berkeley-Designed Chair Cuts Energy Use with Personal Thermal Control." The Daily Californian. September 3, 2013. Available at: http://www.dailycal.org/2013/09/03/uc-berkeley-designed-chair-cuts-energy-use-with-personal-thermal-control/

182 Ackerman, Evan. 2016. "ARPA-E Funding Personal Climate Control Systems with Robots, Foot Coolers, and More." IEEE Spectrum. March 10, 2016. Available at: http://spectrum.ieee.org/energywise/energy/the-smarter-grid/arpae-funding-personal-climate-control-systems-with-robots-foot-coolers-and-more

183 Personal Comfort Systems. Accessed August 2017. Available at: http://www.personalcomfortsystems.com/

184 Thermoregulation Engineering Corp. Website. Accessed August 2017. Available at: http://www.aquonchair.com/#contact

185 Tempronics Website. Accessed August 2017. Available at: http://www.tempronics.com/technology/

186 Gentherm Website. Accessed August 2017. Available at: http://www.gentherm.com/en/page/thermoelectric-heating-cooling

187 Friedlander, Blaine. 2015. "Hot Fashion: DOE Awards $3M Grant for 'Air-Conditioned' Clothing." Cornell Chronicle. January 2015. Available at: http://news.cornell.edu/stories/2015/01/doe-awards-3m-air-conditioned-clothing

188 Fan, Jintu. 2015. "Thermoregulatory Clothing System for Building Energy Saving." Cornell University. ARPA-e DELTA Program Kickoff. May 2015. Available at: https://arpa-e.energy.gov/sites/default/files/08_Cornell_DELTA_Kickoff.pdf

the network of personal comfort systems could signal the central thermostat to adjust itself to a higher temperature set point.[189]

Technical Maturity and Current Developmental Status

Several vendors offer personal comfort devices today, whereas others are still under development. The current generation of products does not have the capabilities to directly interact with the building's HVAC system, so manual temperature adjustments for the central thermostat are necessary.

Barriers to Market Adoption

Product cost and operational complexity present the largest challenges to widespread adoption of these technologies. To truly work within an office or other commercial setting, every occupant must have a personal comfort device at their workstation as well as any other locations. In addition, every device must have an electrical connection to power the device or charge the battery.

Energy Savings Potential

Potential Market and Replacement Applications

As a technology category, personalized comfort devices would be applicable for most commercial building and HVAC system types. Nevertheless, each product type will have target applications that make it more suitable for certain markets (e.g., chairs for an office).

Energy Savings

Research by UC Berkeley with human test subjects suggests that personal comfort devices could maintain user comfort over a much wider air temperature range (64° to 82 °F) than a conventional HVAC system (71° to 75 °F). This suggests that personal comfort systems could enable temperature setback for the central HVAC system, which could achieve 7-14% energy savings.[190,191] These energy savings do not take into account the energy required to charge and/or operate the personal comfort devices. We estimate that personal comfort devices could provide energy savings on the order of 10% if temperature setpoints are relaxed by several degrees throughout the year. Large-scale testing of personal comfort devices within commercial buildings is required to understand these tradeoffs and quantify the energy savings benefits.

Cost and Complexity

The cost of deploying personal comfort devices across an entire building will be high, especially given that there is likely minimal opportunity for HVAC equipment downsizing. Hyperchair is projected to cost around $1,000,[192] which is comparable to high-end office furniture, but is significantly higher than baseline products. As noted previously, current products do not interact with the building's HVAC control system, which adds additional cost and complexity.

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[189] Ackerman, Evan. 2016. "ARPA-E Funding Personal Climate Control Systems with Robots, Foot Coolers, and More." IEEE Spectrum. March 10, 2016. Available at: http://spectrum.ieee.org/energywise/energy/the-smarter-grid/arpae-funding-personal-climate-control-systems-with-robots-foot-coolers-and-more

[190] Hoban, Virgie. 2013. "UC Berkeley-Designed Chair Cuts Energy Use with Personal Thermal Control." The Daily Californian. September 3, 2013. Available at: http://www.dailycal.org/2013/09/03/uc-berkeley-designed-chair-cuts-energy-use-with-personal-thermal-control/

[191] Hoyt et al. 2005. "Energy savings from extended air temperature setpoints and reductions in room air mixing." UC Berkeley. August 2005. Available at: http://escholarship.org/uc/item/28x9d7xj

[192] UC Berkeley. 2016. "Hyperchair Helps Office Employees Control Their Individual Environments." April 2016. Available at: https://ced.berkeley.edu/events-media/news/hyperchair-helps-office-employees-control-their-individual-environments

Peak-Demand Reduction and Other Non-Energy Benefits

The primary benefit of these technologies is more closely controlling the comfort of each individual according to their preferences and current state. Vendors also promote their personal comfort products as productivity aides because past research has shown that both ambient temperature and personal comfort are associated with higher productivity.[193] For technologies that use batteries, the grid-tied electricity demand could decrease during peak events in favor of increased cooling from battery-powered devices.

Next Steps for Technology Development

Building-wide deployment of personalized comfort devices would represent a significant change to how space conditioning and comfort is used in commercial buildings. For these technologies to move from individual systems to building-wide solutions, they must interact as a network to communicate with the building's HVAC controls.

Table 36 lists potential next steps to advance wearable devices for personal comfort.

Table 36: Recommended Next Steps for the Development of Wearable Devices for Personal Comfort

Activities
Conduct laboratory and field testing of personal comfort systems to quantify the comfort and energy savings benefits at different ambient temperature setpoints
Develop and demonstrate next-generation systems that aggregate the status of distributed personal comfort systems and communicate directly with the central HVAC system

[193] Ibid

8 Conclusions

Through this study, we identified 18 high priority technology options for achieving HVAC energy savings in U.S. commercial buildings. This section summarizes the key findings and conclusions on this list, including:

- Technical Energy Savings Potential
- Development Atatus
- Cost and Complexity
- Peak Demand Reduction and Non-Energy Benefits
- Potential Disadvantages.

In addition, we compare the findings of this study with the prior research on commercial HVAC technologies.

8.1 Technical Energy Savings Potential

Figure 34 highlights the technical energy savings potential of the high priority technology options, by technology category. Most of these technologies could reduce the U.S. space cooling and heating energy consumption of commercial buildings (3.81 Quads/yr.) by approximately 10%. Alternative Electrically Driven Heat Pump Technologies provide mostly space cooling energy savings, whereas Alternative Gas-Fired Heat Pump Technologies provide mostly space heating energy savings. The remaining two categories (Technology Enhancements for Current Systems and Alternative System Architectures) provide energy savings for both space cooling and heating.

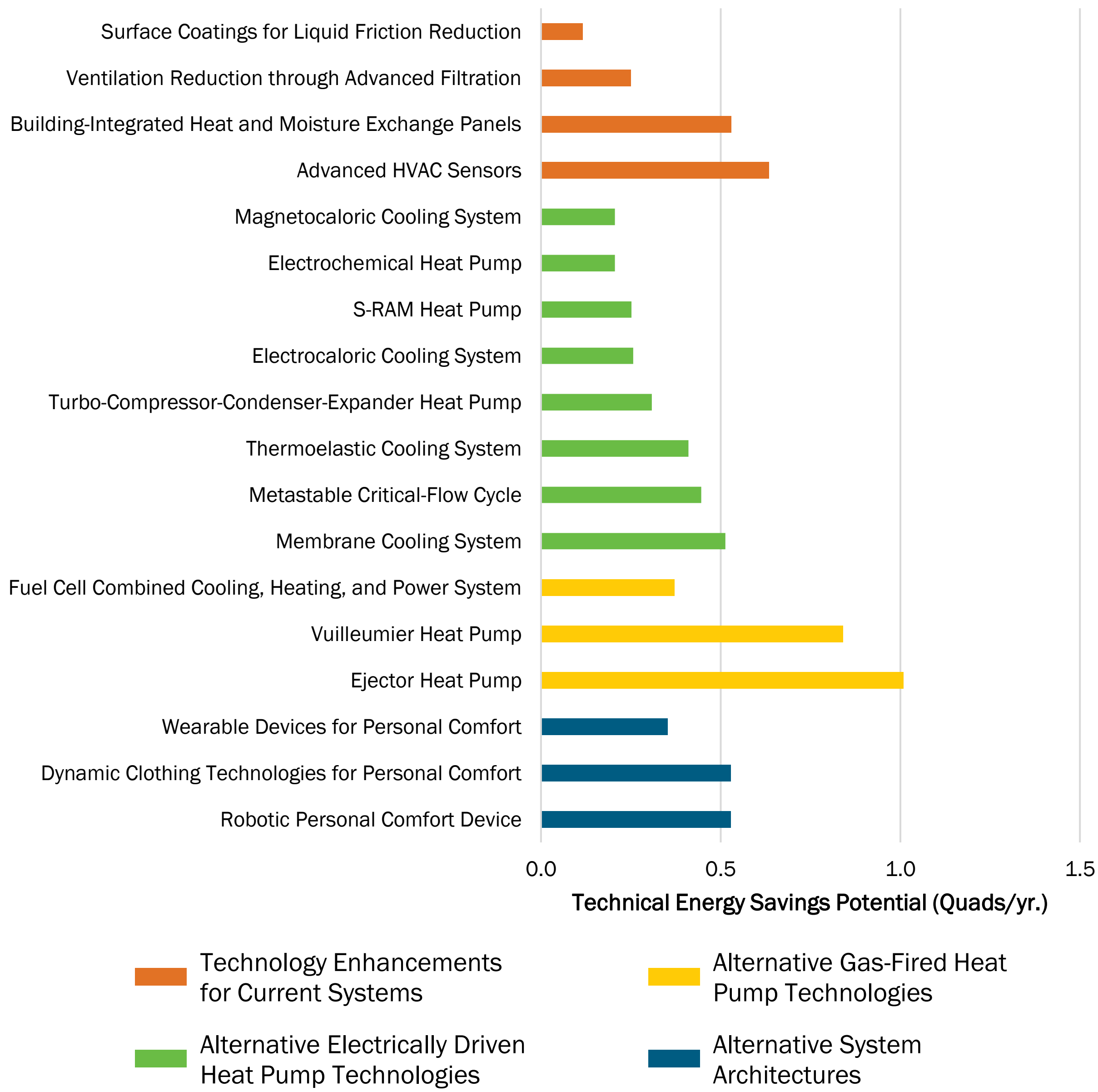

Figure 34: Technical energy savings potential for high priority technologies by technology category

8.2 Development Status

Figure 35 shows the technical energy savings potential of the high priority technology options, by technical maturity. Commercial HVAC energy savings opportunities exist across all technical maturity levels, with several technologies in the initial stages of commercialization. Additional research is necessary to demonstrate the performance of the early-stage technologies and advance their development towards commercial product readiness and market introduction. At this stage, the energy savings projections for early-stage technologies are likely optimistic, as the inevitable tradeoffs that get made to produce practical systems tend to produce some inefficiencies. Furthermore, in scaling up laboratory prototypes to commercial building capacity levels, the electricity consumption of pumps, fans, and other auxiliary loads are often found to be larger than initially anticipated.

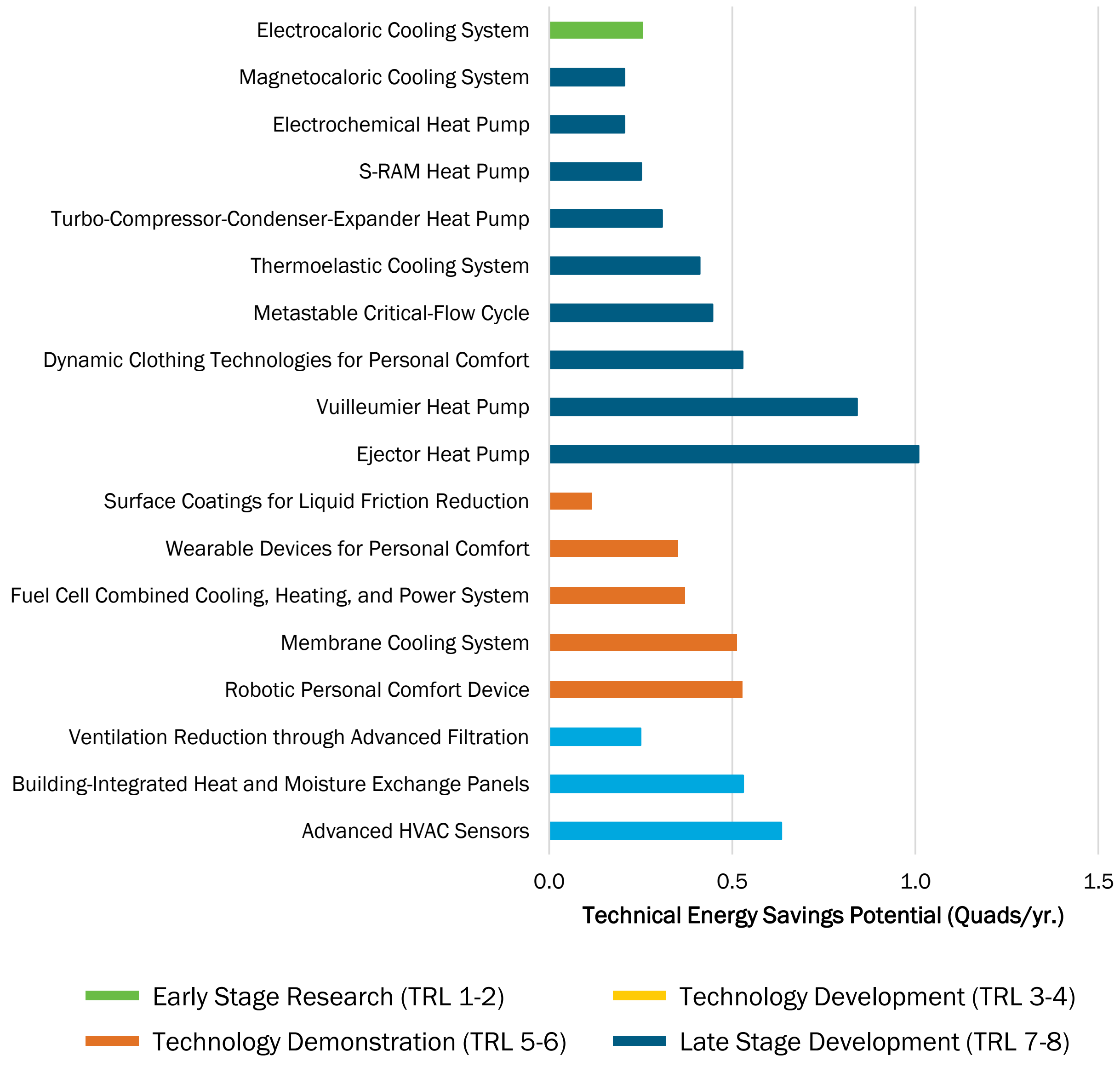

Figure 35: Technical energy savings potential for high priority technologies by technical maturity

8.3 Cost and Complexity

Table 37 highlights the expected cost and complexity of the high priority technology options, by level. Most researchers project reasonable payback periods for these technologies, especially for building applications with high HVAC loads owing to operating hours and climate. Nevertheless, most of these technologies are in the early stages of development, and it is not possible to provide reliable estimates of equipment cost, installation requirements, operating and maintenance costs, etc. Notably, technology developers often project costs based on large economies of scale and mature manufacturing techniques. In reality, these cost projections are often highly uncertain and sometimes assume substantial material science and performance breakthroughs.

Table 37: Estimated Cost/Complexity for Technology Options

Category	Technology Options
Neutral Cost / Complexity	• Metastable Critical-Flow Cycle • S-RAM Heat Pump • Ventilation Reduction through Advanced Filtration • Turbo-Compressor-Condenser-Expander Heat Pump • Surface Coatings for Liquid Friction Reduction
Moderately Higher Cost / Complexity	• Vuilleumier Heat Pump • Advanced HVAC Sensors • Building-Integrated Heat and Moisture Exchange Panels • Membrane Cooling System • Ejector Heat Pump • Thermoelastic Cooling System • Electrochemical Heat Pump • Magnetocaloric Cooling System
Significantly Higher Cost / Complexity	• Robotic Personal Comfort Device • Dynamic Clothing Technologies for Personal Comfort • Fuel Cell Combined Cooling, Heating, and Power System • Electrocaloric Cooling System • Wearable Devices for Personal Comfort

8.4 Peak-Demand Reduction and Non-Energy Benefits

Beyond energy savings, each of the high priority technology options may provide other benefits that are attractive to building owners and operators. Table 38 summarizes the non-energy benefits that the high priority technology options can provide. These benefits may support increased market adoption of the technologies, as many end users would view comfort and IAQ benefits as having a similar – or even greater – level of importance as energy savings.

Reducing the electrical demand of HVAC systems during peak hours is increasingly important for electric utilities and other stakeholders, as late afternoon cooling loads often strain the existing capacity of the electrical grid or the availability of power. Technologies that can reduce the electricity capacity requirements by using natural gas (e.g., gas-fired heat pump) or shifting electricity consumption to off-peak hours (e.g., battery storage for personal comfort devices) would have a significant benefit to both grid operators and, through lower demand charges or peak-hours consumption, building owners. In addition, utilities with high electrical heating adoption on their system experience winter peaking events, and technologies that offer electricity savings during peak winter events are also valuable.

Table 38: Expected Peak Demand and Non-Energy Benefits of the High Priority Technology Options

Technology Option	Key Benefits				
	Peak - Demand	Comfort	IAQ	Low-GWP Working Fluid	Noise
Vuilleumier Heat Pump	✓✓			✓	
Advanced HVAC Sensors		✓			
Robotic Personal Comfort Device	✓✓	✓			
Building-Integrated Heat and Moisture Exchange Panels			✓		
Membrane Cooling System		✓	✓	✓	
Metastable Critical-Flow Cycle				✓	✓
Ejector Heat Pump	✓✓			✓	
Dynamic Clothing Technologies for Personal Comfort	✓	✓			
Thermoelastic Cooling System				✓	✓
S-RAM Heat Pump				✓	
Fuel Cell Combined Cooling, Heating, and Power System	✓✓	✓	✓	✓	✓
Ventilation Reduction through Advanced Filtration	✓✓		✓		
Turbo-Compressor-Condenser-Expander Heat Pump				✓	
Electrocaloric Cooling System				✓	✓
Wearable Devices for Personal Comfort	✓	✓			
Surface Coatings for Liquid Friction Reduction	✓	✓			
Electrochemical Heat Pump				✓	✓
Magnetocaloric Cooling System				✓	✓

✓ denotes potential benefit

✓✓ denotes significant peak-demand benefit due to fuel switching

8.5 Potential Disadvantages

While non-energy benefits may help increase the adoption of new technologies, major changes to the installation or operating procedures of the HVAC system could pose issues that that impede their market adoption in certain applications. Four types of potential disadvantage, described below, were found relative to the high priority technology options.

1. Several parts of the U.S. have critical water concerns, with high prices and low allowances; introducing HVAC systems with high water consumption may be problematic in those regions with respect to local codes or utility bills.
2. If new technologies require changes to the building envelope, installation costs at existing buildings may become prohibitively expensive.
3. Similarly, technologies with larger size or weight relative to conventional equipment could make installation costs at existing buildings too expensive.
4. New system architectures that require coordination between distributed comfort technologies and the central HVAC system could increase the complexity of the HVAC control system or require new operating procedures. (For example, building security may need to hand out devices to visitors, or IT departments may need to troubleshoot malfunctioning devices.)

Table 39 summarizes the disadvantages that could be presented by high priority technology options. Researchers should keep these potential disadvantages in mind when developing and testing the technologies.

Table 39: Potential Disadvantages for High Priority Technology Options

Technology Option	Potential Disadvantages			
	Size / Weight	Retrofit Challenges	Operational Complexity	Water Consumption
Robotic Personal Comfort Device			✓	
Building-Integrated Heat and Moisture Exchange Panels		✓	✓	
Membrane Cooling System				✓
Metastable Critical-Flow Cycle	✓			
Ejector Heat Pump	✓			
Dynamic Clothing Technologies for Personal Comfort			✓	
Wearable Devices for Personal Comfort			✓	

✓ denotes potential disadvantage

8.6 Comparison to 2011 Commercial HVAC Study

As discussed in Section 1.2, this study builds upon previous efforts commissioned by DOE BTP that investigated energy-efficient technology options for commercial HVAC systems. Table 40 lists the high priority technology options identified in the 2011 study, noting how we classified those technologies in the present report.[194]

Table 40: Comparison of High Priority Technology Options from Goetzler et al. (2011)

Category	Technology Option	Status in Current Report	Notes
Advanced Component Technologies	Smart Refrigerant Distributors	Included in 2nd Round	
	Thermoelectrically Enhanced Subcoolers	Included in 2nd Round	Combined with Thermoelectric Cooling System
Alternative Heating & Cooling Technologies	Liquid Desiccant A/C	Included in 2nd Round	
	Magnetic Cooling Cycle	High Priority Technology Option	
	Solar Enhanced Cooling	Included in 2nd Round	Combined with Solar Thermal Cooling System
	Solar Ventilation Preheating	Included in 2nd Round	Combined with Solar Thermal Cooling System
	Thermoelectric Cooling Cycle	Included in 2nd Round	
	Thermotunneling Cooling Cycle	Included in 2nd Round	
Thermal Distribution Systems	Aerosol Duct Sealing	Included in 2nd Round	
	Demand Controlled Ventilation	Included in 2nd Round	
	Duct-Leakage Diagnostics	Included in 2nd Round	Included as part of Unitary Fault Detection and Diagnostic System
	Ductwork in Conditioned Space	Screened in 1st Round	Design decision commercialized
	Thermal Displacement Ventilation	Included in 2nd Round	
Performance Optimization & Diagnostics	Building Energy Information System	Included in 2nd Round	Included as part of Building Automation System (BAS)
	Continuous Commissioning	Screened in 1st Round	Commercialized process in need of deployment support
	Packaged RTU FDD	Included in 2nd Round	Included as part of Unitary Fault Detection and Diagnostic System
	Retrocommissioning	Screened in 1st Round	Commercialized process in need of deployment support

[194] Goetzler et al. 2011. "Energy Savings Potential and Research, Development, & Demonstration Opportunities for Commercial Building Heating, Ventilation, and Air Conditioning Systems." Navigant Consulting Inc. Prepared for BTO. September 2011. Available at: https://energy.gov/sites/prod/files/2014/07/f17/commercial_hvac_research_opportunities.pdf

We included and assessed each of the 2011 technology options as part of the initial list, but several were screened from further consideration due to the current increased focus on early-stage technology development. Many of these technologies (e.g., retro-commissioning, ductwork in conditioned space) still offer large energy savings when incorporated into existing buildings.

Most of the technologies were analyzed as part of the preliminary research and analysis phase; brief summaries are included in the appendices. One technology, magnetic cooling cycle, is in the high priority list of both reports, which highlights its continued need for technical improvement and its market attractiveness for building HVAC and other applications.

8.7 Summary of Observations

The key results of these analyses are listed below:

- We reviewed a wide range of technologies for commercial HVAC applications and identified 18 high priority technology options that could provide large-scale energy savings for U.S. commercial buildings.
- The high priority technology options are in various stages of development, ranging from early prototype development to early commercialization, and they offer energy savings in space cooling applications, space heating applications, or both.
- Most of the technologies can provide substantial non-energy benefits (e.g., improved comfort and IAQ, use of low-GWP refrigerants) or reduce electricity demand during peak hours, which will increase their attractiveness in the marketplace.

9 Recommendations

Based on our review of the high priority technology options for commercial HVAC systems, we recommend that DOE BTO and industry stakeholders pursue the RD&D activities outlined in this section. Most of the high priority technology options are in the early stages of benchtop testing and prototype development, and therefore require sustained RDR&D support to reach market introduction and subsequent wider commercialization. As such, many technologies share a similar development path of component design, laboratory-based testing, prototype development, field testing, and other activities. Table 41 summaries the categories of RD&D activities recommended for the 18 high priority commercial HVAC technology options.

Table 41: Recommended RD&D Activity Categories

Activity Category	Description
Initial Research	Investigations into the fundamental characteristics of heating and/or cooling cycles, properties of specialized materials, and other underlying research areas.
Component Development	Integration of advanced materials, working fluids, and component designs into working subassemblies.
Laboratory Testing	Development of laboratory-scale prototypes and initial testing of major subassemblies to determine performance, efficiency, and other attributes.
Field Demonstration	Installation and testing of complete, integrated prototypes in laboratory test chambers and commercial building pilot locations.
System Integration	Research to refine and integrate components and technologies into viable commercial building HVAC systems, new or existing. Includes steps to improve manufacturability, communication with building controls, installation complexity, size, weight, and other key characteristics.
Deployment Support	Creation of modelling tools, case studies, and other resources that allow building owners, system designers, and other stakeholders to evaluate the technology for their specific applications.

Below we describe in greater depth our recommendations within each category of RD&D activity, with a description of recommended key activities and outcomes, plus stakeholder roles, for each applicable technology. In general, DOE has a primary role in supporting the initial laboratory R&D of early-stage technologies, with industry organizations supporting product demonstrations and deployment strategies. Nevertheless, most of the activities outlined in this section will require collaboration with research organizations, manufacturers, utilities, and other industry organizations.

9.1 Initial Research RD&D Activities

1. Conduct laboratory research on the fundamental physics of the metastable critical-flow cycle.

Applicable Technology Options: Metastable Critical-Flow Cycle

Researchers have made progress on characterizing the supersonic multi-phase fluid flow of the metastable critical-flow cycle, as well as identifying strategies to improve temperature rise, capacity, and efficiency through advanced nozzle designs. Additional research is necessary to evaluate these hypotheses through further analysis and experimentation. We recommend that stakeholders continue R&D efforts to improve the fundamental understanding of the metastable critical-flow cycle, to further inform R&D on optimized nozzle designs and initial prototype development.

2. Continue research into advanced caloric materials.

Applicable Technology Options: Electrocaloric, Magnetocaloric, and Thermoelastic (Elastocaloric) Cooling Systems

Several "caloric" cooling technologies (electrocaloric, magnetocaloric, and elastocaloric) have shown promising results for low-capacity and low-temperature lift applications, but require further support to meet the performance and operational requirements of commercial HVAC applications. Research efforts like the CaloriCool consortium are exploring a wide range of potential caloric materials to identify and/or synthesize materials with improved properties for various applications.[195] We recommend continued research into bettering advanced caloric materials through understanding of their material properties, testing their performance, evaluating their manufacturability, and other relevant activities. Researchers should then continue R&D on different caloric cooling system concepts incorporating the improved materials.

9.2 Component Development RD&D Activities

3. Continue development and testing of advanced membrane-based components.

Applicable Technology Options: Membrane Cooling System, Electrochemical Heat Pump, Fuel Cell Combined Cooling, Heating, and Power System

Several promising technology options use advanced membranes to efficiently transfer moisture between two fluid streams to drive the cooling cycle. Membrane cooling and desiccant systems generate space cooling by removing humidity from air across a membrane and evaporating water to sensibly cool air. The electrochemical heat pump pressurizes the hydrogen working fluid across a proton exchange membrane. The membranes employed by these technologies must have high reliability to operate in non-ideal conditions for numerous years. They must integrate with standard components in HVAC systems (e.g., joining to aluminum, copper, and other materials). Furthermore, they must achieve a relatively low cost at high-volume production. A recent BTO report outlined several research areas that stakeholders identified as important for continued membrane technology development for various building applications, including HVAC.[196] We recommend continued research to improve the performance, reliability, cost, and other key attributes of membrane-based components for HVAC technologies.

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[195] CaloriCool - The Caloric Materials Consortium. Accessed August 2017. Available at: https://caloricool.org/

[196] Goetzler et al. 2017. "R&D Opportunities for Membranes and Separation Technologies in Building Applications." Navigant Consulting Inc. Prepared for BTO. November 2017. Available at: https://www.energy.gov/sites/prod/files/2017/11/f46/DOE-BTO%20Membranes%20Separations%20Report%20Nov%202017.pdf

4. ***Conduct research to improve binary-fluid and ejector geometry selection for different applications*.**

Applicable Technology Options: Ejector Heat Pump

Ejectors are increasingly available for automotive, industrial, and commercial refrigeration systems, but researchers have noted that the design constraints and operating conditions of HVAC systems (e.g., temperatures, efficiency, size) have proved challenging for ejector heat pumps. New ejector heat pump concepts show potential for HVAC energy savings, but they require additional research to determine high-performing working fluid pairs and nozzle designs for various applications. We recommend further analytical modelling and experimental evaluation to improve high-performing ejector heat pump components for commercial HVAC applications.

5. ***Continue development of low-cost, wireless HVAC sensor technologies*.**

Applicable Technology Options: Advanced HVAC Sensors

Distributing low-cost, low-power sensors throughout a commercial building could increase the operational awareness and energy saving capabilities of HVAC control systems. Today's HVAC sensors can adequately maintain comfortable temperatures, but incorporating networks of sensors (ideally self-powered) can enable more precise temperature control of individual rooms or zones. Such networks can also improve the accuracy and precision of building occupancy information, which would improve temperature and humidity control as well as equipment scheduling. Several sensor platforms and wireless networks under development could change how buildings gather and communicate information, but additional research is necessary to cost-effectively bring these technologies to market. We recommend continued research into the technical development and manufacturability of low-cost sensor technologies incorporating advanced capabilities such as: wireless communication; easy installation (e.g., peel-and-stick); self-configuring, -commissioning, -calibration, and -healing; and energy harvesting.

6. ***Develop fabrics incorporating different dynamic clothing technology concepts*.**

Applicable Technology Options: Dynamic Clothing for Personal Comfort

Researchers are currently investigating several advanced materials and fabrics that dynamically change their properties in response to changes in ambient temperatures and other outside stimuli. These dynamic clothing technologies could potentially provide commercial HVAC energy savings by maintaining indoor occupant comfort at HVAC temperature set points that save energy but are traditionally considered uncomfortable (e.g., a higher set point in summer for space cooling savings). While these concepts will face a number of operational and logistic challenges, we recommend continued research into these dynamic clothing technologies for building HVAC and other applications. Even if the fabrics are not successful for wide-scale building thermostat setting changes, the technologies could be applied in localized space heating/cooling configurations, or in special-purpose garments for inside or outside use.

9.3 Laboratory Testing RD&D Activities

7. ***Conduct laboratory testing with benchtop prototypes to understand the performance and efficiency of the technology and guide future development*.**

Applicable Technology Options: Surface Coatings for Liquid Friction Reduction, Membrane Cooling System, Metastable Critical-Flow Cycle, Thermoelastic Cooling System, S-RAM Heat Pump, Electrocaloric Cooling System, Magnetocaloric Cooling System

Many of the high priority technology options profiled in this report are currently under development and/or study in research laboratories, with no or limited application as part of a complete system. In most cases, individual components have been experimentally tested, with results interpreted by analytical models to project full-scale performance. We recommend that researchers develop benchtop prototypes of these technologies with a heating, cooling, or ventilation capacity relevant to building HVAC systems. This experimentation will provide insight into the strengths and limitations of current embodiments of the technology, identify key research needs, and guide the next stages of product development.

8. Conduct laboratory testing with full-scale prototypes to understand performance and efficiency when including auxiliary loads.

Applicable Technology Options: Turbo-Compressor-Condenser-Expander Heat Pump, Vuilleumier Heat Pump, Ejector Heat Pump, Fuel Cell Combined Cooling, Heating, and Power System, Robotic Personal Comfort Device

For several high priority technology options, researchers have demonstrated the feasibility of the core technology using laboratory benchtop prototypes, but have not tested systems installed in usage-relevant environments. While the laboratory environment allows for better control over important variables, prototype tests of that kind often make assumptions about the energy consumption of auxiliary loads (e.g., fans, pumps). In general, they also do not account for tradeoffs in product packaging to achieve size, weight, and other requirements relevant to usage in commercial buildings. We recommend that stakeholders develop full-scale prototypes designed for commercial building applications, in order to: (a) better evaluate the performance, efficiency, and operating characteristics, and (b) identify and understand important real-life design tradeoffs. This development phase will help identify any technical, market, or operating challenges before installation at commercial demonstration sites.

9. Conduct laboratory research on occupant comfort preferences when using alternative system architectures.

Applicable Technology Options: Robotic Personal Comfort Device, Dynamic Clothing Technologies for Personal Comfort, Wearable Devices for Personal Comfort

The alternative system architectures listed work with the centralized HVAC system to satisfy a building occupant's comfort needs, and would present a radical change for commercial building controls. Researchers have studied indoor comfort preferences extensively and have developed standards such as ASHRAE Standard 55[197] to ensure proper conditions. However, these technologies represent a new category of providing comfort to which current research and solutions most likely not closely applicable. We recommend that technology developers conduct research with volunteer occupants in controlled environments, to understand the energy efficiency, comfort, and other tradeoffs between their technologies and the centralized HVAC system. This research will help identify key performance indicators, which will inform design specifications for further evaluation and selection by HVAC system designers.

[197] ASHRAE Website. "Pursuing Thermal Comfort: Ensure Standard 55 Compliance with Latest User's Manual." Accessed August 2017. https://www.ashrae.org/resources--publications/bookstore/standard-55-and-user-s-manual

9.4 Field Demonstration RD&D Activities

10. Conduct field demonstrations in commercial buildings with pre-production technology prototypes.

Applicable Technology Options: Advanced HVAC Sensors, Building-Integrated Heat and Moisture Exchange Panels, Ventilation Reduction through Advanced Filtration, Surface Coatings for Liquid Friction Reduction, Membrane Cooling System, S-RAM Heat Pump, Magnetocaloric Cooling System, Vuilleumier Heat Pump, Fuel Cell Combined Cooling, Heating, and Power System

As noted above, most of the high priority technology options are at the laboratory experimentation stage, with only a few having commercial-ready products for initial market introduction. We recommend that technology developers conduct several rounds of field demonstration in commercial buildings to understand: (a) their technology's performance over time and in different building types and climate zones, and (b) the experiences of building operators and HVAC technicians regarding installation, maintenance, and repair. The demonstrations would also identify key packaging and component/control integration requirements for commercial-ready products, and provide case studies for future discussions with building owners and HVAC system designers.

11. Conduct field demonstrations of alternative system architectures with different temperature set point schedules.

Applicable Technology Options: Robotic Personal Comfort Device, Dynamic Clothing Technologies for Personal Comfort, Wearable Devices for Personal Comfort

While these products under development will provide comfort to an individual occupant, the alternative system architecture technologies can only provide energy savings when they permit thermostat adjustments, e.g., by being deployed across an entire building. Because the personal comfort technologies will operate in conjunction with the building's centralized HVAC systems, there will be a balance point at which further energy savings from the thermostat temperature setback overcomes any energy consumption by the personal-comfort products. This balance point will likely depend on the specific personal-comfort technology, building type, central HVAC system design, and other parameters. We recommend that technology developers conduct field demonstrations of alternative system architectures, testing different temperature set points and schedules to better understand the balance point for actual commercial buildings. This will also help them understand the operational requirements of their technologies when deployed across an entire building.

9.5 System Integration RD&D Activities

12. Collaborate with manufacturers to integrate surface coatings into their production processes.

Applicable Technology Options: Surface Coatings for Liquid Friction Reduction

Specialized surface coatings under development today show promise to reduce liquid and frost buildup on fin-and-tube heat exchangers, which could improve energy efficiency and reliability. While some researchers envision field-applied coatings to retrofit HVAC systems, most see the technology being applied during heat exchanger manufacture so that new systems and components would include the coating before installation. An automated factory application process would have lower cost, greater uniformity, and wider adoption than field application methods, which would improve both cost-effectiveness and national energy savings. We recommend that surface coating technology developers collaborate with HVAC equipment and component manufacturers on integration of the technology into equipment production processes.

13. Collaborate with building automation and HVAC controls vendors to integrate technologies into building controls systems.

Applicable Technology Options: Advanced HVAC Sensors, Robotic Personal Comfort Device, Dynamic Clothing Technologies for Personal Comfort, Wearable Devices for Personal Comfort

The listed technology options have the potential to improve the operation of centralized HVAC systems in commercial buildings, but this requires coordination with building automation (BAS) and controls vendors to ensure full integration with building controls systems. BAS vendors would incorporate the advanced HVAC sensors and networks into their product offerings. For alternative system architecture technologies, the vendors would design software that can communicate with the personalized comfort technologies and adjust the set points and schedules of traditional HVAC controls systems. For example, the BAS system could coordinate with the robotic personal comfort devices to find the best temperature set point to accommodate both personal and building-wide comfort. Because these systems will enhance the current HVAC controls infrastructure, we recommend technology developers form partnerships with BAS and HVAC controls suppliers during the R&D process to coordinate on communication standards, demonstrations, and controls platform development.

9.6 Deployment Support RD&D Activities

14. Develop spreadsheet and building modelling tools for HVAC system designers.

Applicable Technology Options: Building-Integrated Heat and Moisture Exchange Panels, Vuilleumier Heat Pump, Fuel Cell Combined Cooling, Heating, and Power System

The technology options listed above could improve the performance and energy efficiency of commercial buildings, beyond HVAC savings alone. These technologies can provide water heating savings (Vuilleumier Heat Pump), improve thermal insulation and outside air delivery (Building-Integrated Heat and Moisture Exchange Panels), and generate electricity on-site for use by other building systems. Building owners and HVAC system designers must estimate the energy and economic impacts of both HVAC and non-HVAC benefits when determining the cost-effectiveness of these technologies. Therefore, we recommend that building modelling software (e.g., EnergyPlus) incorporate these technologies as standard equipment and system options, so building designers can estimate their impacts on whole-building performance. In addition, we recommend the creation of spreadsheet tools that can quickly calculate the energy and economic impacts of the technologies for different building types, climate zones, utility rates, and other factors.

15. Collaborate with building code agencies and other stakeholders to increase the feasibility of projects.

Applicable Technology Options: Building-Integrated Heat and Moisture Exchange Panels, Ventilation Reduction through Advanced Filtration, Fuel Cell Combined Cooling, Heating, and Power System

The listed technology options have the potential for large national energy savings in commercial buildings, but differ from traditional HVAC system designs and operations. In some cases, these technologies may conflict with existing state or local building codes that provide prescriptive guidance on required outside air rates, ventilation system locations, on-site generation system siting, and other attributes. We recommend that stakeholders work with code agencies at different levels (industry, national, state, and local) to understand how these technologies would be interpreted under current building code guidance, and to develop strategies to encourage code revisions as necessary in future years.

Appendix A: Technology Option Scoring

A.1 High Priority Technology Options

Table 42 provides scoring for the high priority technology options, including those that are widely commercialized and not included as part of the final list of 18 high priority technology options.

Table 42: Scoring Results for High Priority Technology Options

Technology Option	Technology Maturity	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction	Final Score
		50%	15%	15%	15%	5%	
Vuilleumier Heat Pump	4	5	2	3	3	5	3.95
Advanced HVAC Sensors	2	5	2	3	3	3	3.85
Building Automation System	1	5	2	3	3	3	3.85
Max Tech Fans	1	5	2	3	3	3	3.85
Robotic Personal Comfort Device	3	5	1	2	4	5	3.80
Membrane Cooling System	3	5	2	2	3	3	3.70
Building-Integrated Heat and Moisture Exchange Panels	2	5	2	2	3	3	3.70
Max Tech Equipment	1	5	1	3	3	3	3.70
Metastable Critical-Flow Cycle	4	4	3	3	4	3	3.65
Ejector Heat Pump	4	5	2	2	2	5	3.65
Dynamic Clothing Technologies for Personal Comfort	4	5	1	1	3	3	3.40
Demand Controlled Ventilation	1	4	2	3	3	3	3.35
Smart Airflow Balancing for RTUs	1	4	2	3	3	3	3.35
Thermoelastic Cooling System	4	4	2	2	4	3	3.35
Adsorption Heat Pump	1	4	2	2	4	3	3.35
S-RAM Heat Pump	4	3	3	4	4	3	3.30

Technology Option	Technology Maturity	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction	Final Score
		50%	15%	15%	15%	5%	
Advanced Thermostat	1	3	3	4	3	4	3.20
Absorption Heat Pump	1	4	1	2	4	3	3.20
Fuel Cell Combined Cooling, Heating, and Power System	3	4	1	1	4	5	3.15
Ventilation Reduction through Advanced Filtration	2	3	3	3	3	5	3.10
Rapid Building Energy Modeler	1	3	3	4	2	3	3.00
Phase Change Materials	1	3	2	3	3	5	2.95
Turbo-Compressor-Condenser-Expander Heat Pump	4	3	3	2	3	3	2.85
Acoustic Fault Detection	1	3	2	3	3	3	2.85
Electrocaloric Cooling System	5	3	1	3	4	3	2.85
Max Tech Motors	1	3	2	3	2	3	2.70
Wearable Devices for Personal Comfort	3	3	1	2	3	4	2.60
Variable Refrigerant Flow and Ductless Heat Pumps	1	3	2	1	4	1	2.60
Surface Coatings for Liquid Friction Reduction	3	2	3	3	3	4	2.55
Magnetocaloric Cooling System	4	2	2	3	4	3	2.50
Electrochemical Heat Pump	4	2	2	3	4	3	2.50
Chilled Beam Radiant Cooling System	1	2	1	4	4	3	2.50
Thermal Displacement Ventilation	1	2	1	3	5	3	2.50

A.2 Lower Priority Technology Options

Table 43 highlights the scoring for lower priority technology options.

Table 43: Scoring Results for Lower Priority Technology Options

Technology Option	Technology Maturity	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction	Final Score
		50%	15%	15%	15%	5%	
Thermoelectric Cooling System	4	1	3	5	4	3	2.45
Large Diameter Destratification Fan	3	1	3	5	4	3	2.45
Improved Terminal Radiant Device	3	2	1	4	3	3	2.35
Smart Air Registers	3	2	3	2	3	3	2.35
Aerosol Duct and Building Envelope Sealing	2	2	3	2	3	3	2.35
Hydrocarbon Refrigerants	2	2	4	1	3	3	2.35
Unitary Fault Detection and Diagnostic System	1	2	2	3	3	3	2.35
Baopt Pulse Cooling Control	1	2	2	3	3	3	2.35
Miniaturized Microchannel Heat Exchanger	4	2	3	3	2	3	2.35
HFO Refrigerants	2	1	3	3	5	3	2.30
BoostHEAT Boiler	3	3	1	1	2	3	2.25
Electrohydrodynamic Heat Transfer	4	2	2	2	3	3	2.20
Centrifugal Compressors for RTUs	3	2	1	3	3	3	2.20
Nanofiber Air Filter	1	2	2	3	2	3	2.20
Mixed-Mode Conditioning	1	2	2	2	3	3	2.20
Advanced Hydronic Heating Valve	2	2	2	2	3	3	2.20
Engine-Driven Heat Pump	1	2	2	2	2	5	2.15
Bernoulli Cooling Cycle	4	1	3	3	4	3	2.15
Rotating Spool Compressor	3	1	4	4	2	3	2.15

Technology Option	Technology Maturity	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction	Final Score
		50%	15%	15%	15%	5%	
Solar Thermal Cooling System	1	2	1	1	4	5	2.15
UV Light Treatment	1	1	2	4	4	3	2.15
Radiative Cooling Panel	3	2	1	2	3	4	2.10
Rotary Vapor-Compression Heat Pump	4	2	2	2	2	3	2.05
Adaptive Refrigerant Charge Control	3	2	2	2	2	3	2.05
Desiccant-Coated Heat Exchanger	5	2	3	1	2	3	2.05
Bio Air Filtration	3	2	2	1	3	3	2.05
Thermotunneling Cooling System	5	1	1	4	4	3	2.00
Carbon Dioxide Heat Pump	3	1	2	3	4	3	2.00
Serpentine Heat Exchanger	3	1	3	3	3	3	2.00
Occupant Comfort Feedback Control	1	1	2	4	3	3	2.00
Advanced Chiller Control Valve	1	1	2	4	3	3	2.00
Chiller with Water Refrigerant	1	1	2	3	4	3	2.00
Brayton Heat Pump	1	1	2	3	4	3	2.00
Condensing RTU	2	2	1	2	2	3	1.90
Thermoacoustic Cooling System	4	1	1	3	4	3	1.85
Synchronous and Notched Fan Belts	1	1	3	3	2	3	1.85
Unitary Thermal Storage System	3	2	1	1	2	5	1.85
Evaporative Condenser	1	2	1	2	1	5	1.85
Dual Stirling Engine Heat Pump	4	1	1	2	4	5	1.80
Thermosyphon Cooling Tower	2	1	2	2	4	1	1.75
Metal Foam Heat Exchanger	4	1	3	2	2	3	1.70
Nanoparticle Refrigerant Additives	4	1	2	3	2	3	1.70

Technology Option	Technology Maturity	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction	Final Score
		50%	15%	15%	15%	5%	
Metal Wire Heat Transfer Enhancement	4	1	2	3	2	3	1.70
Improved Heat Pipes	4	1	2	3	2	3	1.70
Heat-Recovery RTU for Water Pre-Heating	2	1	1	2	4	3	1.70
Demand Controlled Kitchen Ventilation	1	1	2	3	2	3	1.70
Improved Heat Pump Defrost	3	1	2	2	2	3	1.55
Cold-Climate Heat Pump	3	1	1	2	2	3	1.40
Solar PV Cooling System	1	1	1	1	2	5	1.35
Liquid Desiccant Cooling System	4	1	1	1	2	3	1.25
Smart Refrigerant Distributor	4	1	1	1	2	3	1.25

Appendix B: Descriptions of Commercialized High Priority Technology Options

B.1 Max Tech Fans

Technology Description	Commercial HVAC systems utilize fans for a variety of applications, including: supply fans in air-handling units (AHUs), RTUs, exhaust fans, fan coil units, condenser fans, cooling tower fans, and many other applications. A 2015 BTO report estimated that commercial HVAC fans account for roughly 2.0 Quads of primary energy annually. Significant opportunities exist to reduce the energy consumption of commercial HVAC fans, including: motor upgrades, VFDs, improved blade and housing designs, better sizing and selection, regular maintenance, and other options. In total, the 2015 BTO report estimated these measures could save over 70% of HVAC fan energy consumption in the U.S.[198]				
Unit Energy Savings	70%	Unit energy savings for commercial fan consumption from 2015 BTO report			
Technical Energy Savings Potential	1,400 TBtu	Estimated commercial fan consumption[199]			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
3.85	5	2	3	3	3

B.2 Building Automation System

Technology Description	Building automation and energy management systems (BAS/EMS) help commercial HVAC systems achieve high performance and energy efficiency by implementing the operators control strategy, gathering performance and energy data, providing fault detection and diagnostic (FDD) capabilities for equipment and systems, benchmarking energy consumption, and other services. The systems can be installed either during new construction or retrofit, and may cover whole building loads or focus on the HVAC system. Studies have shown that proper use of BAS and EMIS systems can save individual buildings 17% or greater when performed correctly. Traditionally, such systems mostly focused on larger buildings, but vendors are now offering retrofit solutions for smaller commercial buildings, particularly those with long hours and high energy requirements like retail and food service.[200]	
Unit Energy Savings	17%	Estimate from LBNL report
Technical Energy Savings Potential	599 TBtu	All HVAC cooling and heating consumption

[198] Guernsey et al. 2015. "Pump and Fan Technology Characterization and R&D Assessment." Navigant Consulting Inc. Prepared for DOE BTO. October 2015. Available at: https://energy.gov/sites/prod/files/2015/10/f27/bto_pumpfan_report_oct2015.pdf
[199] Ibid
[200] Granderson and Lin. 2016. "Building Energy Information Systems: Synthesis of Costs, Savings, and Best-Practice Uses." LBNL. February 2016. Available at: https://eetd.lbl.gov/sites/all/files/1006431_0.pdf

Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
3.85	5	2	3	3	3

B.3 Max Tech Equipment

Technology Description	Manufacturers have continued to improve the energy efficiency and performance of their commercial HVAC products. Today, the highest performing commercial boilers offer efficiencies up to 99%, gas-fired unit heaters and make-up air (MUA) units reach 93%, RTUs up to 17.5 SEER / 20.8 IEER, and commercial chiller efficiencies below 0.50 kW/ton full load and 0.30 kw/ton IPLV. Demonstrating the energy savings of these technologies and developing programs to promote and incentivize their adoption could considerably save energy for commercial HVAC systems in future years simply on equipment replacement.				
Unit Energy Savings	20% heating 30% cooling	Based on comparison of manufacturer literature			
Technical Energy Savings Potential	853 TBtu	All commercial HVAC energy consumption			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
3.70	5	1	3	3	3

B.4 Smart Airflow Balancing for RTUs

Technology Description	Several vendors have created zone airflow control systems that combine WiFi-connected dampers and zone-level thermostats. The zone thermostats communicate with the main RTU controller and dampers modulate the amount of airflow entering each zone. The technology could provide HVAC energy savings of 20%-30% by more precisely meeting the comfort needs of each zone or room. A recent case study by the utility Nicor Gas showed the technology's promising energy savings potential.[201]
Unit Energy Savings	20% — Estimate from manufacturer literature and field studies
Technical Energy Savings Potential	496 TBtu — HVAC energy consumption, except chillers, for all building types except large office and healthcare buildings
Technology Readiness Level (TRL)	Full Commercialization

[201] Rowley et al. 2016. "Emerging Technology Program #1077: Dynamic Air Balancing System." Gas Technology Institute. Prepared for Nicor Gas Company. December 2016. Available at: https://www.nicorgasrebates.com/-/media/Files/NGR/PDFs/ETP/1077%20Dynamic%20Air%20Balancing%20Public%20Project%20Report%20FINAL%2012-12-2016.pdf

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
3.35	4	2	3	3	3

B.5 Demand Controlled Ventilation

Technology Description	Demand Controlled Ventilation (DCV) is a control method which involves automatic adjustment of the ventilation system based on presence of occupants in a building space. Systems usually use IR or carbon dioxide sensors to determine occupancy in a room or zone. Many building codes now require DCV for new buildings, but retrofit controllers are available for existing RTU and MUA systems.[202] Recent developments include utilization of other volatile organic compounds (VOCs) sensors that can improve comfort and IAQ.				
Unit Energy Savings	15%	Estimated 15-20% savings based on field studies			
Technical Energy Savings Potential	372 TBtu	HVAC energy consumption for all building types except large office and healthcare buildings			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
3.35	4	2	3	3	3

B.6 Adsorption Heat Pump

Technology Description	Adsorption heat pumps utilize porous materials that capture a vapor refrigerant either on their surface or within their structure to drive a refrigeration cycle. Unlike the vapor-compression cycle, the adsorption cycle is not continuous, but relies on the cyclical adsorbing of vapor into the material or bed, and desorbing the vapor from the bed with a high-temperature heat source. During the desorbing process, the working fluid achieves high temperature and pressure and drives the refrigeration cycle in place of an electrically driven compressor. Gas-fired burners, solar thermal collectors, or waste heat commonly provide the thermal energy to drive adsorption systems. Products are available for residential and light commercial space heating and/or cooling as well as large commercial chillers. Products are more common in Europe and other markets, with several BTO R&D efforts underway to improve their performance and cost effectiveness for U.S. market.[203] While space cooling COPs are generally lower than vapor-compression cycles (0.4-0.7), space heating COPs can exceed those of traditional gas-fired technologies (COPs 1.1-1.4).[204]

[202] PNNL. 2012. "Demand Control Ventilation." August 2012. Available at: https://www.energycodes.gov/sites/default/files/documents/cn_demand_control_ventilation.pdf
[203] DOE. 2017. "Residential Gas-Fired Cost-effective Triple-State Sorption Heat Pump." Accessed August 2017. Available at: https://energy.gov/eere/buildings/downloads/residential-gas-fired-cost-effective-triple-state-sorption-heat-pump
[204] Goetzler et al. 2014. "Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies." Navigant Consulting Inc. Prepared for DOE BTO. March 2014. Available at: https://energy.gov/sites/prod/files/2014/03/f12/Non-Vapor%20Compression%20HVAC%20Report.pdf

Unit Energy Savings	36%	36% assuming 1.25 COP vs. 0.80 COP baseline			
Technical Energy Savings Potential	393 TBtu	All gas furnace heating			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
3.35	4	2	2	4	3

B.7 Advanced Thermostat

Technology Description	Small (5,000 sq.ft.) and medium commercial buildings (5,000-50,000 sq.ft.) often use simplified control strategies for HVAC and other buildings in place of a full BAS / EMS. These control strategies (e.g., 7-day programmable thermostat) are effective, but leads to unnecessary energy consumption by lacking occupancy sensing, benchmarking, FDD, DR, remote connectivity, and other capabilities. A 2012 PNNL study projects 10-25% energy savings by upgrading the unsophisticated building controls in small to medium buildings to those more common in larger buildings.[205] Products specifically designed for these building segments are increasingly available including residential-style smart thermostats to low-cost EMS for specific building segments (e.g., retail, foodservice).				
Unit Energy Savings	10%	Estimate based on PNNL report			
Technical Energy Savings Potential	248 TBtu	Commercial HVAC energy consumption for all building types except large office and healthcare buildings			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
3.20	3	3	4	3	4

[205] Katipamula et al. 2012. "Small- and Medium-Sized Commercial Building Monitoring and Controls Needs: A Scoping Study." PNNL. October 2012. Available at: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-22169.pdf

B.8 Absorption Heat Pump

Technology Description	Absorption systems use thermal energy to drive a heat-pump cycle where a refrigerant is cyclically absorbed and desorbed from a secondary fluid. Depending on the configuration, absorption HPs can be designed as heating-only, cooling-only, or reversible (both heating and cooling). Although cooling efficiencies are typically less than those for vapor-compression systems, absorption HPs offer large potential energy and cost savings, especially for space heating heating-dominated climates with COPs of 1.4 and greater. Products are available today for commercial space heating applications, but absorption systems still carry a substantial cost premium related to their size, weight, and operational requirements and are not suitable for all commercial HVAC applications. For example, today's products are mostly hydronic systems, which poses issues for light commercial buildings with packaged RTUs. Research is underway to reduce cost, weight, complexity, etc. through advanced heat exchanger designs, working fluids, and other advancements with a goal of wide adoption for space and water heating.[206]				
Unit Energy Savings	40%	Estimated 40% savings based on absorption heat pump COP of 1.4 vs. 0.8 for baseline products			
Technical Energy Savings Potential	436 TBtu	All gas furnace heating			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
3.20	4	1	2	4	3

B.9 Rapid Building Energy Modeler

Technology Description	Developed by LBNL and licensed to the start-up Indoor Reality, the portable Rapid Building Energy Modeler (RAPMOD) system creates a 3D indoor map of buildings using laser scanners, optical and thermal cameras, and other sensors to allow for quicker and less expensive energy auditing and other use cases. A user walks around the building wearing the backpack collecting data, which is then uploaded to building energy simulation software to better predict energy efficiency opportunities. The backpack system is intended to lower the cost for accurate energy auditing, to then increase the use of building energy auditing, and ultimately retrocommission buildings more often. By performing these activities more frequently, commercial buildings can maintain high performance and reduce energy consumption.[207]

[206] (a) Gluesenkamp et al. 2017. "Theory of Semi-Open Sorption Gas-Fired Heat Pump Systems and Early Experimental Results." ORNL. ACEEE Hot Water Forum. February 2017. Available at: http://aceee.org/sites/default/files/pdf/conferences/hwf/2017/Gluesenkamp_Session5B_HWF17_2.28.17.pdf
(b) Geoghegan, Patrick. 2017. "Commercial Absorption Heat Pump Water Heater." ORNL. 2017 Building Technologies Office Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/4_32226e_Geohagen_031417-1000.pdf
(c) Garrabrant, Michael. 2016. "Low-Cost Gas Heat Pump for Building Space Heating." Stone Mountain Technologies Inc. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/312105_Garrabrant_040716-915.pdf
[207] (a) Indoor Reality Website. Accessed August 2017. Available at: http://www.indoorreality.com/
(b) Zakhor, Avideh. 2017. "Fast, Automated Building Energy Auditing." ARPA-e. January 2017. Available at: https://arpa-e.energy.gov/sites/default/files/documents/files/RAPMOD%20Impact%20Sheet-01272017_FINAL.pdf

Unit Energy Savings	16%	Estimated 16% for retrocommissioning, but does not decrease energy consumption directly			
Technical Energy Savings Potential	242 TBtu	HVAC energy consumption for large office, assembly, and education buildings			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
3.00	3	3	4	2	3

B.10 Phase Change Materials

Technology Description	Phase change materials (PCMs) provide passive cooling by storing and releasing thermal energy as latent heat. PCMs are substances such as paraffin or salts that undergo a phase change (from solid to liquid and back) near the desired building temperature. Deploying these materials in buildings can help maintain a consistent indoor temperature, as excess heat is absorbed by the PCM during daytime and released at nighttime. A 2013 NREL study looking at PCMs in residential building envelopes estimated 15-20% cooling energy savings.[208] Researchers are studying how to encapsulate PCMs and apply them to interior building surfaces, either as finished panels or as a thin coating materials integrated into wall paint or drywall.[209]				
Unit Energy Savings	9%	Estimate for commercial buildings			
Technical Energy Savings Potential	317 TBtu	All commercial HVAC energy consumption			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.95	3	2	3	3	5

(c) Seidenman, Pam. 2014. "Rapid Building Energy Modeller." LBNL. 2014. Available at: http://www.arpae-summit.com/paperclip/exhibitor_docs/14AE/Lawrence_Berkeley_National_Laboratory_188.pdf

[208] Kosny et al. 2013. "Cost Analysis of Simple Phase Change Material-Enhanced Building Envelopes in Southern U.S. Climates." NREL. January 2013. Available at: https://www.nrel.gov/docs/fy13osti/55553.pdf

[209] Eitner and Tröster. 2016. "BAU 2017: Pleasant Indoor Climate due to Phase Change Materials Combination of Insulation and Thermal Mass." Fraunhofer. December 2016. Available at: https://www.fraunhofer.de/content/dam/zv/en/press-media/2016/Dezember/ForschungKompakt/rn_12_2016_ICT_Combination%20of%20Isolation%20and%20thermal%20mass.pdf

B.11 Acoustic Fault Detection

Technology Description	Two start-up companies, VirtJoule and Augury, have developed sensor packages for RTUs, chillers, large fans/pumps, and other major equipment that can detect faults and poor performance through acoustic or vibration signatures. VirtJoule is a retrofit sensor kit that continuously monitors electricity consumption, runtime, and vibration to fault detection when performance deviates from expected conditions.[210] Service technicians can use Augury's magnetic sensors to periodically measure the health of equipment through their acoustic/vibration signature, benchmark to previous measurements, and receive a diagnosis of potential issues.[211] The technologies are designed for preventive maintenance programs and project 20% energy savings by quickly finding and repairing poor performance.[212]				
Unit Energy Savings	20%	Estimated 20% by finding causes of poor performance quickly			
Technical Energy Savings Potential	231 TBtu	All commercial cooling and heat pump heating energy consumption			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.85	3	2	3	3	3

B.12 Max Tech Motors

Technology Description	Commercial HVAC systems use a variety of motors for outdoor and supply fans, water pumps, compressors, dampers, and other functions, and account for a high percentage of HVAC system energy consumption. Technologies such as advanced motor designs, VFDs, and controls are available for high performance buildings and equipment, and deploying these technologies more widely could save upwards of 30% on motor related energy consumption for different end uses, for 9% savings across all areas.[213] Research is underway to develop new motor designs to offer high performance at lower cost to reach a wider segment of the commercial building stock.	
Unit Energy Savings	9%	Estimated savings for total commercial HVAC motor from 2013 BTO Motors Report
Technical Energy Savings Potential	302 TBtu	Based on HVAC motor energy consumption from 2013 BTO Motors Report[214]
Technology Readiness Level (TRL)	Full Commercialization	

[210] Virtjoule Website. Accessed August 2017. Available at: http://www.virtjoule.com/
[211] Augury Website. Accessed August 2017. Available at: http://www.augury.com/industries/buildings/
[212] Metz, Rachel. 2015. "This Gadget Can Tell What's Wrong with Your Air Conditioner by Listening to It." MIT Technology Review November 2015. Available at: https://www.technologyreview.com/s/543786/this-gadget-can-tell-whats-wrong-with-your-air-conditioner-by-listening-to-it/
[213] Goetzler et al. 2013. "Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment." Navigant Consulting Inc. Prepared for DOE BTP. December 2013. Available at: https://energy.gov/sites/prod/files/2014/02/f8/Motor%20Energy%20Savings%20Potential%20Report%202013-12-4.pdf
[214] Goetzler et al. 2013. "Energy Savings Potential and Opportunities for High-Efficiency Electric Motors in Residential and Commercial Equipment." Navigant Consulting Inc. Prepared for DOE BTP. December 2013. Available at: https://energy.gov/sites/prod/files/2014/02/f8/Motor%20Energy%20Savings%20Potential%20Report%202013-12-4.pdf

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.70	3	2	3	2	3

B.13 Variable Refrigerant Flow and Ductless Heat Pumps

Technology Description	Variable refrigerant flow (VRF) systems and other ductless heat pumps are split-system A/Cs that use refrigerant piping, not ducts, to exchange energy between the 'outdoor' and 'indoor' side of the system. By eliminating ducts to distribute thermal energy, the technology reduces fan energy consumption and loss of thermal energy to duct leakage in unconditioned spaces. VRF systems provide a unique feature in that they can serve as both a heating and cooling system simultaneously, by recovering heat from an area being cooled (i.e. a server room) and delivering this 'free' energy to an area requiring heating (i.e. an office on the north-facing windows of the building). Adopted widely throughout the world, several foreign and domestic manufacturers offer VRF and ductless heat pump products in the U.S., but currently hold lower market position relative to conventional RTU and other systems. VRF systems provide an estimated 30% energy savings over baseline conventional commercial HVAC systems, but this will vary by building application.[215]				
Unit Energy Savings	25%	Estimate based on reduced duct losses and heat recovery potential			
Technical Energy Savings Potential	289 TBtu	All commercial cooling and heat pump heating energy consumption			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.60	3	2	1	4	1

B.14 Chilled Beam Radiant Cooling System

Technology Description	Radiant cooling systems circulate chilled water through ceiling-mounted 'chilled beams' to provide sensible cooling for buildings. The technology can provide energy savings by reducing fan consumption, using more efficient chiller temperatures, and other strategies, but the benefits will differ by individual building. A dehumidification device is usually warranted in tandem with a radiant cooling system because condensate will either accumulate on the floor or ceiling. Systems can be passive or active, where active systems rely on an air stream from another source (such as a DOAS unit or other dehumidification / ventilation device) to induce airflow onto the ceiling radiant cooling coil, which significantly increases cooling capacity beyond that of passive beams.[216]

[215] Thornton and Wagner. 2012. "Variable Refrigerant Flow Systems." Prepared for the General Services Administration By Pacific Northwest National Laboratory. December 2012. Available at: https://www.gsa.gov/portal/mediaId/197399/fileName/GPG_Variable_Refrigerant_Flow_12-2012.action

[216] Trane. 2011. "Understanding Chilled Beam Systems." 2011. Available at: https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/education-training/engineers-newsletters/airside-design/adm_apn034en_1209.pdf

Unit Energy Savings	25%	Estimate based on case studies			
Technical Energy Savings Potential	146 TBtu	All chiller-type commercial cooling systems.			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.50	2	1	4	4	3

B.15 Thermal Displacement Ventilation

Technology Description	Displacement ventilation is an air distribution strategy that introduces cool air into a zone at low velocity, usually at low level. Buoyancy forces naturally carry the ventilation air upward, pooling fresh air in the breathing zone of the room. This strategy can improve ventilation efficiency relative to conventional ceiling-based systems. Displacement ventilation typically requires that an under-floor or wall-integral system of ventilation ducts be installed in the building, which can then be connected with ventilation air diffusers to be installed at floor level. The strategy provides energy savings by using a more efficient supply air temperature setting and decreasing the required airflow velocity, but will vary by application.[217]				
Unit Energy Savings	21%	Estimate based on case studies			
Technical Energy Savings Potential	126 TBtu	HVAC energy consumption for Variable Air Volume (VAV) ventilation systems			
Technology Readiness Level (TRL)	Full Commercialization				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.50	2	1	3	5	3

[217] Architectural Energy Corporation. 2005. "Design Brief – Displacement Ventilation." August 2005. Available at: https://energydesignresources.com/media/1723/EDR_DesignBriefs_displacementventilation.pdf?tracked=true

Appendix C: Descriptions of Lower Priority Technology Options

C.1 Early Stage Research (TRL 1-2)

C.1 Desiccant-Coated Heat Exchanger

Technology Description	By applying a desiccant such as silica gel or sodium polyacrylate to the surface of a heat exchanger (e.g., an evaporator coil), the desiccant provides latent cooling while the conventional vapor-compression system provides sensible cooling. This strategy would provide more efficient dehumidification and allow a smaller temperature difference between the sensible cooling source and supply air, with significant energy savings projected for hot humid climates. The technology is currently under development and would require regular regeneration of the desiccant either through outside heating source or operating the vapor-compression cycle in reverse similar to a heat pump.[218]				
Unit Energy Savings	50%	Projected savings from laboratory research			
Technical Energy Savings Potential	138 TBtu	Energy consumption for RTU and VAV ventilation systems in hot, humid climate			
Technology Readiness Level (TRL)	Early Stage Research (TRL 1-2)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.05	2	3	1	2	3

C.2 Thermotunneling Cooling System

Technology Description	Thermotunneling cooling systems use an electric voltage to induce a current and a temperature difference across two surfaces. The technology is similar to thermoelectric cooling, but uses a barrier between the two surfaces to reduce resistive heating. Currently, thermotunneling cooling devices are under development for small electronics cooling applications,[219] with limited development of larger capacity systems for building space cooling. Researcher project higher energy efficiency through thermotunneling cooling, but prospects for commercial HVAC systems are unknown.	
Unit Energy Savings	0-5%	No energy savings based on current performance, projected to have some savings if developed
Technical Energy Savings Potential	51 TBtu	All commercial cooling systems except chillers
Technology Readiness Level (TRL)	Early Stage Research (TRL 1-2)	

[218] Tu and Wang. 2016. "Theoretical Investigation of a Novel Unitary Solid Desiccant Air Conditioner." Science and Technology for the Built Environment Volume 23, 2017. November 2016. Available at: http://www.tandfonline.com/doi/full/10.1080/23744731.2017.1251790

[219] Zhang et al. 2006. "On-Chip High Speed Localized Cooling Using Superlattice Microrefrigerators." IEEE Transactions on Components and Packaging Technologies. Vol. 29, NO. 2. JUNE 2006. Available at: http://bears.ucsb.edu/uoeg/publications/papers/Zhang06IEEE.pdf

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.00	1	1	4	4	3

C.2 Technology Development (TRL 3-4)

C.3 Thermoelectric Cooling System

Technology Description	Thermoelectric cooling systems use the Peltier effect where two specialized metals produce a temperature gradient when a voltage is applied across the metals. The solid-state cooling technology is commercially available for small-scale refrigeration and electronics cooling, but has a number of challenges to meeting the temperature differences and efficiencies required for building cooling applications. Nevertheless, researchers are developing advanced systems for refrigeration, water heating, and power generation from energy harvesting, and also as a supplemental subcooling device for vapor-compression systems.[220] The technology is also featured in a number of wearable personal comfort devices (Section 7.3).				
Unit Energy Savings	0-5%	No energy savings based on current performance, projected to have some savings if developed			
Technical Energy Savings Potential	51 TBtu	All commercial cooling systems except chillers			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.45	1	3	5	4	3

C.4 Miniaturized Microchannel Heat Exchanger

Technology Description	The miniaturized air-to-refrigerant heat exchanger is a compact, 3D printed, compact heat exchanger that improves heat transfer, reduces pressure drop, decreased number of joints, and improves cost competitiveness compared to current market designs. The miniaturized HX has at least 20% higher performance, has lower volume, uses less material and lower approach temperature compared to current market designs. Recent work performed by UMD, funded by BTO, has successfully developed prototypes of the next-generation heat exchanger, with a goal of commercial production within 5 years.[221]	
Unit Energy Savings	10%	Estimated 20% improvement in heat exchanger performance, estimated 7-10% savings from full system performance
Technical Energy Savings Potential	116 TBtu	All commercial cooling and heat pump heating energy consumption

[220] Nanalyze. 2016. "8 Thermoelectric Generator and Cooler Startups." September 2016. Available at: http://www.nanalyze.com/2016/09/8-thermoelectric-generator-cooler-startups/

[221] DOE. 2016. "Miniaturized Air to Refrigerant Heat Exchangers." Accessed August 2017. Available at: http://energy.gov/eere/buildings/downloads/miniaturized-air-refrigerant-heat-exchangers

Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.35	2	3	3	2	3

C.5 Electrohydrodynamic Heat Transfer

Technology Description	Electrohydrodynamic heat transfer enhancement involves the use of high voltage (>1 kV), low current, electrodes to increase the fluid motion of refrigerant near the heat exchanger walls. This process reduces thermal resistance and improves heat exchanger performance. In laboratory studies, such systems have improved refrigerant-side heat exchanger coefficients by 100% and greater, but the impacts on overall system performance or actual HVAC systems are not well documented. Current research of this technology focuses on mission-critical applications (e.g., aerospace, high-performance computing) where heat exchanger sizing has greater impact than HVAC applications.[222]	
Unit Energy Savings	10%	Estimated efficiency performance, although likely will reduce heat exchanger size
Technical Energy Savings Potential	162 TBtu	All commercial cooling and heat pump heating energy consumption
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	

Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.20	2	2	2	3	3

C.6 Bernoulli Cooling Cycle

Technology Description	The Bernoulli cooling cycle accelerates a gas refrigerant through a nozzle, which creates a temperature gradient for space cooling and/or heating applications. Proof-of-concept prototypes in early 2010s have demonstrated the cycle's cooling effect with low efficiency, and identified several areas of possible improvement, but lack of funding has hindered further research.[223]	
Unit Energy Savings	0-5%	No energy savings based on current performance, projected to have some savings if developed
Technical Energy Savings Potential	51 TBtu	All commercial cooling systems except chillers
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	

[222] Schlatter, Laurie. 2017. "Beating the Heat in Space." Worcester Polytechnic Institute. January 2017. Available at: https://www.wpi.edu/news/beating-heat-space

[223] Goetzler et al. 2014. "Energy Savings Potential and RD&D Opportunities for Non-Vapor-Compression HVAC Technologies." Navigant Consulting Inc. Prepared for BTO. March 2014. Available at: https://energy.gov/sites/prod/files/2014/03/f12/Non-Vapor%20Compression%20HVAC%20Report.pdf

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.15	1	3	3	4	3

C.7 Rotary Vapor-Compression Heat Pump

Technology Description	Sandia National Labs and partners are developing a rotary vapor-compression heat pump that configures the major components on a common shaft to achieve greater efficiency. The system uses a series of axial fins, connected to a central hub, that transfer heat to and from an airstream when refrigerant flows through the fins. As the assembly rotates, the fins provide the compressive work while also creating airflow across each heat exchanger. The system is currently in conceptual design and testing phase with projected energy savings of 20% or greater at similar cost. The system would operate similar to a RTU to condition air for use within the building. [224]	
Unit Energy Savings	20%	Performance projections from initial R&D
Technical Energy Savings Potential	168 TBtu	RTU cooling and heat pump heating energy consumption
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)	

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.05	2	2	2	2	3

[224] (a) DOE. 2017. “Rotary Vapor Compression Cycle Technology: A Pathway to Ultra-Efficient Air Conditioning, Heating and Refrigeration.” Accessed August 2017. Available at: https://energy.gov/eere/buildings/downloads/rotary-vapor-compression-cycle-technology-pathway-ultra-efficient-air
(b) Kariya, Arthur. 2017. “Rotary Vapor Compression Cycle (RVCC).” Sandia National Laboratories. 2017 Building Technologies Office Peer Review. April 2017. Available at: https://energy.gov/sites/prod/files/2017/04/f34/6_31295_Kariya_031417-1130.pdf

C.8 Thermoacoustic Cooling System

Technology Description	Thermoacoustic cooling systems use high-amplitude sound waves to compress and expand a noble gas, and pump heat between different areas of a sealed resonating chamber. Sound waves generated by a speaker create pressure oscillations that cause the gaseous working fluid to undergo temperature changes as the gas compresses and expands. DOE has funded work at national labs and universities for decades, with few technologies reaching the marketplace. Current prototypes by Sonic Joule / Penn State University (estimated 1.4 COP at refrigeration temperatures)[225] and then ThermoAcoustics / Sound Energy (0.6 COP using solar thermal or other heat source for engine) project less than conventional vapor-compression systems.[226]				
Unit Energy Savings	0-5%	No energy savings based on current performance, projected to have some savings if developed			
Technical Energy Savings Potential	22 TBtu	Chiller energy consumption			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.85	1	1	3	4	3

C.9 Dual Stirling Engine Heat Pump

Technology Description	Stirling heat pumps cyclically compress and expand a gaseous working fluid between two volumes to transfer heat. The motive force for the systems can be generated by an electric motor or a secondary heat engine with gas burner, creating the dual Stirling engine system. A secondary fluid, such as water, connects to these heat sources/sinks through a heat exchanger to then service the space cooling and/or heating loads. Stirling heat pumps operating with electric motors have been commercialized for process cooling, cryocooling, and niche refrigeration applications for several years. Infinia Corporation developed a Stirling-cycle freezer for supermarket refrigeration applications, and its parent company Qnergy has developed a mCHP system as a replacement for boiler systems. We found limited information on the efficiency of fossil-fuel-fired duplex-Stirling heat pumps for space-conditioning applications, especially when factoring in parasitic fan and pump consumption. The Qnergy product has roughly 84% heating efficiency and 15% electrical efficiency, which is comparable to other boiler products, although previous research suggests theoretical COPs of 1.2 for heating and 1.0 for cooling applications.[227]

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[225] (a) Keolian, Robert. 2017. "Thermoacoustic Power Conversion." Sonic Joule. January 2017. Available at: https://arpa-e.energy.gov/sites/default/files/Guest%20Speaker%20-%20Keolian%20-%20For%20Posting.pdf
(b) Keolian et al. 2015. "Trillium: An Inline Thermoacoustic-Stirling Refrigerator." Third International Workshop on Thermoacoustics. October 2015. Available at: http://proceedings.utwente.nl/315/1/TS16.pdf
Available at: https://arpa-e.energy.gov/sites/default/files/Robert%20Keolian%20%28Penn%20State%29.pdf

[226] Sound Energy Website. Accessed August 2017. Available at: http://soundenergy.nl/

[227] (a) Qnergy Website. Accessed August 2017. Available at: https://www.qnergy.com/

Unit Energy Savings	0-5%	No energy savings based on current performance, projected to have some savings if developed			
Technical Energy Savings Potential	51 TBtu	All commercial cooling systems except chillers, and heat pump heating			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
1.80	1	1	2	4	5

C.10 Metal Foam Heat Exchanger

Technology Description	Heat exchangers constructed from tubes passing through metal foam may achieve superior performance compared to conventional fin-and-tube heat exchangers. Due to its high porosity and large specific surface area, open-cell metal foam is an attractive material for heat transfer applications and could potentially offer cost savings through reduced material use. Researchers in Europe are currently developing metal foam heat exchangers and examining the effects of different parameters such as dimensions, flow rate, and porosity on the heat transfer properties of metal foams.[228]				
Unit Energy Savings	0-5%	No energy savings based on current performance, projected to have some savings if developed			
Technical Energy Savings Potential	51 TBtu	All commercial cooling systems except chillers			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
1.70	1	3	2	2	3

(b) Penswick, Barry. 2016. "An Advanced Cooler with Benign Refrigerants." ARPA-e. June 2016. Available at: https://arpa-e.energy.gov/sites/default/files/documents/files/Infinia%20Technology%20Corp%20-%20BEETIT%20External%20Impact%20Sheet_FINAL.pdf

[228] (a) Huisseune et al. 2015. "Comparison of metal foam heat exchangers to a finned heat exchanger for low Reynolds number applications." International Journal of Heat and Mass Transfer. Volume 89. October 2015. Available at: http://www.sciencedirect.com/science/article/pii/S0017931015004962

(b) Hipke, Thomas. 2017. "Metal Foam Center." Fraunhofer IWU. Available at: https://www.iwu.fraunhofer.de/en/metal-foam-center.html

C.11 Nanoparticle Refrigerant Additives

Technology Description	Improving the thermal conductivity of HVAC working fluids can increase the efficiency of a vapor-compression cooling system. Researchers are investigating the potential performance improvements of introducing nano-sized particles such as copper oxide or black carbon in HVAC refrigerants, chiller loops, and other applications. These enhanced fluids have demonstrated improved thermal conductivity at the laboratory scale, but also revealed challenges such as long term stability, high pressure drop, high pumping power, and other performance attributes. Researchers from several institutions are experimenting with nanoparticle refrigerant additives with a goal of optimizing the tradeoff of heat transfer enhancement and increased energy consumption.[229]				
Unit Energy Savings	3%	Based on laboratory testing			
Technical Energy Savings Potential	49 TBtu	All commercial cooling and heat pump heating energy consumption			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
1.70	1	2	3	2	3

C.12 Metal Wire Heat Transfer Enhancement

Technology Description	Researchers at Argonne National Laboratory investigated the use of metal wire inserts in cooling piping to improve the heat transfer effectiveness of their particle accelerator cooling systems. The technology introduces a spiral of metal wire within the cooling pipe for high heat flux applications, so that the cooling water rotates within the pipe and enhances heat transfer. We are unaware of any addition research for chilled water applications for buildings. The technology's heat transfer enhancement would need to overcome any pumping energy penalty.[230]				
Unit Energy Savings	5%	Conservative estimate based on increased heat transfer performance			
Technical Energy Savings Potential	58 TBtu	Energy consumption for chiller and boiler systems			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction

[229] (a) Patil et al. 2015. "Review of the Thermo-Physical Properties and Performance Characteristics of a Refrigeration System Using Refrigerant-Based Nanofluids." Energies Vol. 9. December 2015. Available at: www.mdpi.com/1996-1073/9/1/22/pdf
(b) Majgaonkar, Amey. 2016. "Use of Nanoparticles In Refrigeration Systems: A Literature Review Paper." International Refrigeration and Air Conditioning Conference. July 2016. Available at: http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2703&context=iracc

[230] Collins et al. 2002. "Enhanced Heat Transfer Using Wire-Coil Inserts for HighHeat-Load Applications." Argonne National Laboratory. September 2002. Available at: http://www.ipd.anl.gov/anlpubs/2002/09/44276.pdf

1.70	1	2	3	2	3

C.13 Improved Heat Pipes

Technology Description	Heat pipes are passive devices that transfer heat between two airstreams by evaporating and condensing a refrigerant in a closed series of chambers. Commercial and industrial buildings use heat pipes for heat recovery or dehumidification.[231] Conventional heat pipes utilize a single wick structure to efficiently transport water vapor from the evaporator to the condenser and condensed water droplets back from the condenser. Researchers have developed new heat pipe designs that use a composite multi-layer wick structure to enhance heat recovery in the heat pipe by 56%.[232]				
Unit Energy Savings	2%	Estimated savings from laboratory testing			
Technical Energy Savings Potential	13 TBtu	Energy consumption for RTU and VAV ventilation systems in climate zones 4 and 5			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.70	1	2	3	2	3

C.14 Liquid Desiccant Cooling System

Technology Description	Liquid desiccant cooling systems use specialized liquid salts, lithium chloride or calcium chloride, that absorb water vapor from the supply air stream. The systems provide efficient dehumidification of outdoor air and can couple with a number of secondary sensible cooling stages, such as evaporative or vapor-compression systems. Systems use a gas-fired or solar thermal regenerator to release the captured moisture from the desiccant to continue the cycle. A 2014 NREL report shows liquid desiccant cooling systems providing large energy savings for hot humid climates (34-57%), with lower savings more moderate climates.[233] Liquid desiccant cooling systems are commercially available as standalone dehumidification systems, with several efforts underway to commercialize the technology as a complete building cooling solution. BePowerTech uses the waste heat from a natural gas fuel cell to regenerate a liquid desiccant cooling stage (Section 6.3), and 7AC Technologies is developing a liquid desiccant system using a specialized membrane for heat and mass transfer.[234]

[231] (a) MiTek. 2013. "DHP Wrap-Around Dehumidifier Heat Pipe Systems." Heat Pipe Technology. 2013. Available at: https://www.heatpipe.com/mktg_materials/Brochures/DHP_BROCHURE.pdf
(b) Ong, K.S. 2016. "Review of Heat Pipe Heat Exchangers for Enhanced Dehumidification and Cooling in Air Conditioning Systems." International Journal of Low-Carbon Technologies. Volume 11, Issue 3. September 2016. Available at: https://academic.oup.com/ijlct/article/11/3/416/2198450/Review-of-heat-pipe-heat-exchangers-for-enhanced
[232] Wu and Cheng. 2013. "Heat Pipe with Composite Wick Structure." Patent US 20130160976 A1. June 2013. Available at: https://www.google.com/patents/US20130160976
[233] Kozubal et al. 2014. "Low-Flow Liquid Desiccant Air-Conditioning: Demonstrated Performance and Cost Implications." NREL. September 2014. Available at: https://www.nrel.gov/docs/fy14osti/60695.pdf
[234] 7AC Technologies Website. Accessed August 2017. Available at: http://7actech.com/

Unit Energy Savings	26%	Estimated 12-40% energy savings for hot, humid regions			
Technical Energy Savings Potential	72 TBtu	Energy consumption for RTU and VAV ventilation systems for hot, humid region			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.35	1	1	1	2	3

C.15 Smart Refrigerant Distributor

Technology Description	Smart refrigerant distributes adjust the amount of refrigerant entering each evaporator circuit to account for non-uniform airflow caused by fouling and other issues. As an initial study of the potential for refrigerant circuit-specific flow control, National Institute of Standards and Technology (NIST) studied the potential improvements to HX capacity derived from using needle type expansion valves to individually control the superheat in each circuit of a multi-refrigerant circuit evaporator HX, where varying superheats resulted from an uneven airflow distribution. Researchers at Purdue, NIST, University of Illinois, UMD, and other institutions have investigated smart refrigerant distributor strategies,[235] and manufacturers now offer products for select applications.[236]				
Unit Energy Savings	5%	Estimate based on laboratory research			
Technical Energy Savings Potential	58 TBtu	All commercial cooling and heat pump heating energy consumption			
Technology Readiness Level (TRL)	Technology Development (TRL 3-4)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.25	1	1	1	2	3

[235] (a) Payne and Domanski. 2002. "Potential Benefits of Smart Refrigerant Distributors." NIST. December 2002. Available at: http://fire.nist.gov/bfrlpubs/build02/PDF/b02130.pdf
(b) Bach et al. 2014. "Interleaved Circuitry and Hybrid Control as Means to Reduce the Effects of Flow Maldistribution." International Refrigeration and Air Conditioning Conference. July 2014. Available at: http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2385&context=iracc

[236] Danfoss. 2011. "Most Valves Expand Your Refrigerant EcoFlow Expands Your Options." Danfoss A/S. January 2011. Available at: http://files.danfoss.com/technicalinfo/dila/01/DKRCCPBVJ1A222_520H4039%20revised%20us%20brochure%20(3)%20(1).pdf

C.3 Technology Demonstration (TRL 5-6)

C.16 Large Diameter Destratification Fan

Technology Description	Several manufacturers have developed large diameter fans to reduce air stratification in large, open, indoor spaces with high ceilings. For these buildings, warm air naturally rises to the ceiling, creating large temperature differences between the occupied space near the floor and near the ceiling. The fans improve air circulation, resulting in more thermal energy near occupants for reduced energy consumption. In more temperature seasons, the fans can cool the space by drawing in outside air and exhaust warm air through the ceiling vents.				
Unit Energy Savings	5%	Estimated whole building savings from destratification, will vary by application			
Technical Energy Savings Potential	84 TBtu	All boiler and furnace heating			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.45	1	3	5	4	3

C.17 Improved Terminal Radiant Device

Technology Description	Conventional radiant cooling panels located in ceilings are typically designed to provide only sensible cooling for the space to avoid a situation where condensed water drops onto building occupants or creates wet spots on the floor. Researchers in China are investigating a radiant cooling panel concept with integrated condensate removal system. Researchers estimate heat transfer improvements of 30% and greater, although improvements to overall system energy consumption are uncertain.[237]				
Unit Energy Savings	15%	Based on laboratory research			
Technical Energy Savings Potential	167 TBtu	Chiller and boiler energy consumption			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.35	2	1	4	3	3

[237]Hiawen et al. 2016. "Cooling Performance Test and Analysis of a Radiant-Convective Air Conditioning Terminal Device with Parallel Pipes." 8th International Cold Climate HVAC 2015 Conference. Available at: https://www.researchgate.net/publication/304713372_Cooling_Performance_Test_and_Analysis_of_a_Radiant-convective_Air_Conditioning_Terminal_Device_with_Parallel_Pipes/fulltext/5777ce4508aeb9427e2a198f/304713372_Cooling_Performance_Test_and_Analysis_of_a_Radiant-convective_Air_Conditioning_Terminal_Device_with_Parallel_Pipes.pdf

C.18 Smart Air Registers

Technology Description	Researchers at Stony Book University are developing an active air conditioning vent capable of modulating airflow distribution, velocity, and temperature. The system modulates airflow using an array of electro-active polymer tubes that are individually controlled to create a localized curtain of air to suit an individual's heating or cooling needs. Researchers claim that this technology can be immediately implemented as a replacement for an existing HVAC register or new system. [238]				
Unit Energy Savings	30%	Researcher estimates			
Technical Energy Savings Potential	141 TBtu	HVAC energy consumption for large offices			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.35	2	3	2	3	3

C.19 BoostHEAT Boiler

Technology Description	A new boiler technology from the French company BoostHeat uses a gas-fired Stirling engine to operate a CO_2 heat pump cycle for higher combined efficiency and lower operating cost. Estimated COP for heating of 1.75-2.00, although performance information is not publicly available. The technology requires an air-side condensing unit, in addition to potential engine maintenance. [239]				
Unit Energy Savings	50%	COP >1.75 for natural gas space heating			
Technical Energy Savings Potential	296 TBtu	All gas boiler heating			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.25	3	1	1	2	3

[238] (a) Wang et al. 2015. "electroactive Smart Air-Conditioner Vent Registers (eSAVER) for Improved Personal Comfort and Reduced Electricity Consumption." Stony Brook University. Available at: https://arpa-e.energy.gov/sites/default/files/06_SUNY_DELTA_Kickoff.pdf
(b) ARPA-e. 2014. "Electroactive Smart Air-Conditioner Vent Registers (eSAVER) for Improved Personal Comfort and Reduced Electricity Consumption." December 2014. Available at: https://arpa-e.energy.gov/?q=slick-sheet-project/electroactive-smart-air-conditioner-vent-registers-esaver

[239] (a) BoostHEAT Website. Accessed August 2017. Available at: http://www.boostheat.com/en/the-heat-boiler/
(b) Dujardin, Phillippe. 2016. "boostHEAT." Green Days International Technology & Business Meetings. November 2016. Available at: https://www.b2match.eu/greendays2016-pollutec/participants/578
(c) EHPA. 2015. "EHPA welcomes BoostHeat." European Heat Pump Association. May 2015. Available at: http://www.ehpa.org/about/news/article/ehpa-welcomes-boostheat/

C.20 Centrifugal Compressors for RTUs

Technology Description	Centrifugal compressors provide high efficiency operation for large water-cooled chillers, but have traditionally been impractical for lower capacity systems typical for commercial RTUs. Developing a small centrifugal compressor for 5-20-ton RTUs and other commercial HVAC systems would offer a projected 30% energy savings over conventional systems with scroll compressors. BTO is currently funding R&D at UTRC and Mechanical Solutions / Lennox to develop small centrifugal compressors for the next generation of low-GWP refrigerants.[240]				
Unit Energy Savings	30%	Based on R&D projections			
Technical Energy Savings Potential	223 TBtu	RTU cooling energy consumption			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.20	2	1	3	3	3

C.21 Rotating Spool Compressor

Technology Description	A spool compressor uses a rotating compression mechanism made up of a central vane and hub that forms a rotating spool. The donut-shaped spool is mounted to the vane, offset of center, so as to produce both a constantly rotating compression pocket and suction pocket as the vane rotates. Current research suggests up to a 10% improvement in isentropic efficiency over scroll compressors, but the main benefit of the technology would be lower manufacturing cost. Torad Engineering is developing the technology with researchers at Purdue University.[241]				
Unit Energy Savings	5%	Based on laboratory research			
Technical Energy Savings Potential	81 TBtu	All commercial cooling and heat pump heating energy consumption			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.15	1	4	4	2	3

240 Bennett, Edward. 2017. "Low-GWP HVAC System with Ultra-Small Centrifugal Compression." Mechanical Solutions Inc. 2017 Building Technologies Office Peer Review. April 2017.Available at: https://energy.gov/sites/prod/files/2017/04/f34/2_312107_Bennett_031517-1100.pdf

241 Torad Engineering Website. Accessed August 2017. Available at: http://toradengineering.com/resources/white-papers/

C.22 Radiative Cooling Panel

Technology Description	Researchers at Stanford University and the start-up SkyCool Systems have developed radiant cooling panels that could serve as a more efficient heat rejection system in chilled water and other space cooling systems.[242] The panels use specialized materials with low absorptivity and high emissivity to reflect incoming sunlight and transfer radiant energy from the surface. As a heat rejection system, the panels can decrease their surface temperature approximately 5 °C below ambient air, which could provide a more efficient heat exchanger to remove heat from water or refrigerant working fluid. The panels could also provide sensible cooling for the building in conjunction with a traditional space cooling system. PNNL analyzed the potential for this technology to increase HVAC system efficiency and found 20-30% or greater energy savings.[243,244] The start-up SkyCool is developing the panels and is currently conducting field trials with utility partners.[245]				
Unit Energy Savings	30%	Estimates based on PNNL study and vendor literature			
Technical Energy Savings Potential	152 TBtu	Cooling systems for mercantile, food sales, large office, and warehouse type buildings that would have sufficient roof space			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.10	2	1	2	3	4

C.23 Adaptive Refrigerant Charge Control

Technology Description	Adaptive refrigerant charge control systems modulate the amount of refrigerant in HVAC systems to maintain peak performance in changing conditions. The system uses a series of sensors connected to a control valve to modulate the amount of refrigerant leaving the receiver. Under development by AdvanTek Consulting Engineering, field tests of the technology show energy savings of 15- 40% when installed on existing RTUs.[246]	
Unit Energy Savings	15%	Conservative estimate based on field studies
Technical Energy Savings Potential	154 TBtu	All commercial cooling systems except chillers

[242] SkyCool Systems Website. Accessed August 2017. Available at: http://skycoolsystems.com/
[243] Fernandez et al. 2015. "Energy Savings Potential of Radiative Cooling Technologies." PNNL. November 2015. Available at: http://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24904.pdf
[244] Kubota, Taylor. 2017. "Stanford Professor Tests a Cooling System that Works without Electricity." Stanford University. September 2017. Available at: http://news.stanford.edu/2017/09/04/sending-excess-heat-sky/
[245] Baccei, Bruce. 2016. "SkyCool – Radiant Cooling to Deep Space, Night & Day!" Energy Central. December 2016. Available at: http://www.energycentral.com/c/ee/skycool-%E2%80%93-radiant-cooling-deep-space-night-day
[246] (a) West, Michael. 2015. "Package DX Units: Performance Optimization & Field Tests." Advantek Consulting Engineering, Inc. Available at: https://energy.gov/sites/prod/files/2015/11/f27/fupwg_fall2015_west.pdf
(b) AdvanTek. 2012. "U.S. Department of Defense, ESTCP." Accessed August 2017. Available at: http://www.advantekinc.com/projects-estcp.php

Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.05	2	2	2	2	3

C.24 Bio Air Filtration

Technology Description	The roots of certain plants contain compounds that can absorb indoor contaminants like VOCs and CO_2. Several interior architectural firms have incorporated ventilation systems into specially designed "living wall" systems to use the plant roots as an air filter. By removing indoor air contaminants, the building could decrease outside air requirements, reducing space conditioning energy consumption for ventilation. The products from Nedlaw Living Walls and Skidmore Owings and Merrill claim up to 60% lower outside air requirements, with an end goal of 10-20% energy savings, but have not been adequately demonstrated.[247]				
Unit Energy Savings	10%	Estimate based on case studies			
Technical Energy Savings Potential	151 TBtu	HVAC energy consumption for large office, assembly, and education buildings			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.05	2	2	1	3	3

[247] (a) Labarre, Suzanne. 2012. "SOM's Giant Vertical Flower Pot Is An Air Purifier On Steroids." Co.Design. February 2012. Available at: https://www.fastcodesign.com/1669116/som-s-giant-vertical-flower-pot-is-an-air-purifier-on-steroids
(b) Darlington, Alan. 2016. "Energy Conservation and Related Cost Savings with Indoor Air Biofilters." Nedlaw Living Walls. March 2016. Available at: http://www.nedlawlivingwalls.com/wp-content/uploads/Energy-Conservation-and-Related-Cost-Savings-with-Indoor-Air-Biofilters.pdf
(c) Leber, Jessica. 2016. "This Living Wall Cleans The Air Inside New York's New Emergency Center." Fast Company. July 2016. Available at: https://www.fastcompany.com/3061449/this-living-wall-cleans-the-air-inside-new-yorks-new-emergency-center

C.25 Carbon Dioxide Heat Pump

Technology Description	Carbon dioxide (R-744) is an attractive refrigerant for future commercial HVAC&R applications due to its low GWP (1), but introduces additional design complexities due to its high operating pressure, lower cooling capacity, and lower thermodynamic cycle efficiency at high ambient temperatures. Large commercial refrigeration systems (e.g., cold storage, supermarket racks) have seen the largest adoption of CO_2-based systems, but manufacturers also offer products for space and domestic water heating globally, and as well as chilled water applications in Europe.[248] For space heating, CO_2 heat pumps would provide approximately 20% energy savings with heating COPs of 4-5 or greater.[249]				
Unit Energy Savings	20%	Space heating energy savings for heat pumps assuming COP of 4-5			
Technical Energy Savings Potential	19 TBtu	Heat pump heating energy consumption			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.00	1	2	3	4	3

C.26 Serpentine Heat Exchanger

Technology Description	The serpentine heat exchanger design concept could significantly reduce refrigerant leakage in HVAC systems by reducing the number of joints. The design includes a novel "dog-bone" fin concept that results in an equivalent or better heat transfer performance than current designs with 90% less joints. Optimized Thermal Systems, Inc. is currently developing the initial prototypes for the design.[250]				
Unit Energy Savings	0-5%	Savings unknown, but projected for reduced refrigerant leakage			
Technical Energy Savings Potential	58 TBtu	All commercial cooling and heat pump heating energy consumption			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.00	1	3	3	3	3

[248] Dürr thermea. 2017. "HHR - the right technology matters." Accessed August 2017. Available at: https://www.durr-thermea.com/en/cooling
[249] Wilson, Alex. 2013. "A Heat Pump Using Carbon Dioxide as the Refrigerant." BuildingGreen. August 2013. Available at: https://www.buildinggreen.com/blog/heat-pump-using-carbon-dioxide-refrigerant
[250] Bacellar, Daniel. 2017. "Advanced Serpentine Heat Exchangers." Optimized Thermal Systems, Inc. 2017 Building Technologies Office Peer Review. Available at: https://energy.gov/sites/prod/files/2017/04/f34/1_32293_Bacellar_031517-1000.pdf

C.27 Unitary Thermal Storage System

Technology Description	Large commercial buildings with chillers have used thermal energy storage systems for decades to reduce peak demand during daytime hours.[251] Unitary thermal energy storage can provide significant energy savings and peak demand reduction by operating the packaged RTU at night to generate cooling for use during peak daytime hours. The systems cool water to create ice or solidify a wax material overnight to then melt during the day for space cooling. Systems save substantial electricity costs by using nighttime off-peak electricity rates, and can achieve 5-15% energy savings by operating during cooler nighttime temperatures. IceEnergy has deployed their RTU systems with major manufacturers in California and other markets[252], and NREL is working with the startup NetEnergy to develop its polymer/wax based thermal battery technology.[253]				
Unit Energy Savings	15%	Estimate based on ASHRAE article[254]			
Technical Energy Savings Potential	111 TBtu	Commercial RTU cooling energy consumption			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
1.85	2	1	1	2	5

C.28 Improved Heat Pump Defrost

Technology Description	During cold weather operation, heat pumps must periodically reverse the flow of refrigerant to defrost the outside heat exchanger coils. Researchers at UMD are investigating a new defrost strategy that reverses the airflow for the outdoor unit to more efficiently remove melted water from the coil. The strategy could decrease the number of required defrost cycles, reducing system energy consumption in heating mode.[255]	
Unit Energy Savings	44%	Estimate based on laboratory research
Technical Energy Savings Potential	2 TBtu	Estimated savings for heat pump defrost cycles, which occur an estimated 5% of annual operating hours
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)	

[251] Rutberg et al. 2013. "Thermal Energy Storage." ASHRAE Journal. June 2013. Available at: http://www.calmac.com/stuff/contentmgr/files/0/6ea8b22e25785dca1450b086a73c4df7/pdf/save_energy__money_ashrae_journal_june_2013.pdf
[252] IceEnergy. 2016. "IceBear30." March 2016. Available at: https://www.ice-energy.com/wp-content/uploads/2016/03/ICE-BEAR-30-Product-Sheet.pdf
[253] NETenergy Website. Accessed August 2017. Available at: http://www.netenergytes.com/
[254] Rutberg et al. 2013. "Thermal Energy Storage." ASHRAE Journal. June 2013. Available at: http://www.calmac.com/stuff/contentmgr/files/0/6ea8b22e25785dca1450b086a73c4df7/pdf/save_energy__money_ashrae_journal_june_2013.pdf
[255] Muthusubramanian et al. 2016. "An Experimental Study on Energy Saving Analysis in the Defrost Cycle of Residential Heat Pumps with the Use of Reverse Air Flow during Defrost." Journal Science and Technology for the Built Environment Vol. 23, Issue 4. October 2016. Available at: http://www.tandfonline.com/doi/abs/10.1080/23744731.2016.1239469?scroll=top&needAccess=true&journalCode=uhvc21

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
1.55	1	2	2	2	3

C.29 Cold-Climate Heat Pump

Technology Description	In recent years, electric utilities in the northwest and northeast have heavily promoted cold-climate air-source heat pumps (CCHPs) in the residential sector. Technology enhancements allow residential CCHPs to achieve superior heating performance (both capacity and efficiency) at low outdoor temperatures, compared to conventional residential heat pumps. Similar technology enhancements, mainly variable-speed compressors and fans with overspeed compressor operation in heating mode, are also being applied to commercial unitary air-source heat pumps, allowing these products to offer similar energy-efficiency benefits. United Technologies Research Center (UTRC) has been developing a CCHP RTU since 2013 under the support of the BTO ET program.[256] The project has performance goals of 2.5 COP at -13°F with < 15% capacity degradation for the 10-ton prototype. Laboratory testing shows current COPs of 1.8 for -13°F, 2.7 for 17°F, and 3.9 for 47°F, which suggests that the full product would likely exceed the 1.75 COP at 5° threshold for CCHP performance.[256] The UTRC team is now working with Carrier to potentially commercialize the product, and also plans to begin a demonstration with the DOD Environmental Security Technology Certification Program (ESTCP) program in 2018.[257]				
Unit Energy Savings	25%	Projected savings based on low-temperature performance			
Technical Energy Savings Potential	24 TBtu	Heat pump heating energy consumption			
Technology Readiness Level (TRL)	Technology Demonstration (TRL 5-6)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
1.40	1	1	2	2	3

[256] Mahmoud, Ahmad. 2016. "High-Efficiency Commercial Cold Climate Heat Pump." UTRC. 2016 Building Technologies Office Peer Review. April 2016. Available at: https://energy.gov/sites/prod/files/2016/04/f30/312104_Mahmoud_040716-945.pdf

[257] Mahmoud, Ahmad. 2017. "High-Performance Air-source Cold Climate Heat Pump (CCHP)." UTRC. ESTCP. 2017. Available at: https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Conservation-and-Efficiency/EW-201721

C.4 Late Stage Development (TRL 7-8)

C.30 Aerosol Duct and Building Envelope Sealing

Technology Description	Aeroseal has adapted their aerosol duct sealing technology for use on residential and commercial building envelopes for both existing and new construction applications. The aerosol spray is released within a pressurized space and automatically finds and fills cracks around walls, doors, and windows. Current field demonstrations for the technology in single- and multi-family installations show up at an 80% reduction in air leakage, which provides a 10-25% reduction in HVAC energy consumption. In addition, the technology reduces installation time by 50% or greater, and automatically verifies performance. The DOD ESCTP is currently conducting a field demonstration for the technology.[258]				
Unit Energy Savings	15%	Estimate based on field studies for residential buildings			
Technical Energy Savings Potential	227 TBtu	HVAC energy consumption for large office, assembly, and education buildings			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.35	2	3	2	3	3

C.31 Hydrocarbon Refrigerants

Technology Description	Hydrocarbon refrigerants are attractive due to their low GWP (e.g., propane [R-290] has GWP of 3), but pose a number of issues for commercial HVAC systems due to their flammability. Because 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. As such, hydrocarbon refrigerants have been limited to small capacity A/C systems like room A/Cs, but have seen adoption for commercial refrigeration applications (e.g., reach-ins, self-contained display cases) where charge size and safety measures can overcome flammability risks. Research suggests modest energy savings for commercial A/C systems if products could meet safety standards.[259]	
Unit Energy Savings	7.5%	Estimate of 5-10% based on literature review

[258] (a) MNCEE. 2016. "Demonstrating the Effectiveness of an Aerosol Sealant to Reduce Multifamily Envelope Air Leakage." December 2016. Available at: https://www.mncee.org/getattachment/Resources/Projects/Using-an-Aerosol-Sealant-to-Reduce-Multi-Unit-Dwel/Executive-Summary-2017-02-01.pdf.aspx
(b) Bohac et al. 2016. "Using an Aerosol Sealant to Reduce Multifamily Envelope Leakage." 2016 ACEEE Summer Study on Energy Efficiency in Buildings. August 2016. Available at: http://aceee.org/files/proceedings/2016/data/papers/1_1014.pdf
(c) DOE. 2016. "Field Trial of an Aerosol-Based Enclosure Sealing Technology." Building America Case Study. May 2016. Available at: https://energy.gov/sites/prod/files/2016/06/f32/field-trial-enclosure-sealing-tech.pdf
(d) Modera, Mark. 2015. "Automated Aerosol-Sealing of Building Envelopes." ESTCP. 2015. Available at: https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Conservation-and-Efficiency/EW-201511

[259] Cool Technologies Website. Accessed August 2017. Available at: http://www.cooltechnologies.org/content/efficiency-comparisons-between-hydrocarbons-and-fluorocarbons#_ftn4

Technical Energy Savings Potential	112 TBtu	All commercial space cooling energy consumption			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.35	2	4	1	3	3

C.32 HFO Refrigerants

Technology Description	Hydrofluoroolefins (HFO) are a class of synthetic refrigerants which offer the potential for lower GWP than conventional HFC refrigerants. Manufacturers now offer chillers, mobile AC, and refrigeration products using R-1234yf, R-1234ze, R-514, and other HFO refrigerants, and are exploring the use of HFOs like R-452B, R-477B, and others for packaged A/C applications.[260] Research suggests these technologies will have similar or improved efficiency to current technologies once fully developed.[261] Because most pure HFO and HFO-blend refrigerants are classified as A2L mildly flammable refrigerants under ASHRAE Standard 34, additional R&D is necessary to ensure safe operation in commercial buildings.				
Unit Energy Savings	5%	Estimate based on laboratory testing with “soft optimization”			
Technical Energy Savings Potential	81 TBtu	All commercial vapor-compression HVAC systems			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.30	1	3	3	5	3

[260] Yana Motta, Samuel. 2017. “Low GWP Alternatives for Commercial AC Applications.” Honeywell. Climate and Clean Air Coalition. 2017. Available at: http://ccacoalition.org/sites/default/files/2017_technology-airconditioning-workshop_SessionIIB_Yana%20Motta.pdf

[261] Chemours. 2016. “Opteon XL55 Refrigerant.” The Chemours Company. 2016. Available at: https://www.chemours.com/Refrigerants/en_US/products/Opteon/Stationary_Refrigeration/assets/downloads/Opteon_XL55_prodinfo.pdf

C.33 Advanced Hydronic Heating Valve

Technology Description	Advanced hydronic control valves maintain an optimal temperature difference in the hydronic heating systems, and allow the circulator pump to turn down its speed in response to reduced load. Each hydronic coil uses an automated valve connected with a heat sensor, and the valve position adjusts to maintain an optimal temperature difference between the supply and return lines. The main system circulator also monitors the temperature difference across the boiler and adjusts pumping speed to maintain an optimal temperature difference between the supply and return lines. This technology has been demonstrated in two college campus buildings, and ORNL is conducting a pilot demonstration at a government facility.[262]				
Unit Energy Savings	30%	Estimate based on vendor literature			
Technical Energy Savings Potential	160 TBtu	Based on HVAC pump energy consumption from 2015 BTO Pumps and Fans Report[263]			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.20	2	2	2	3	3

C.34 Condensing RTU

Technology Description	Condensing furnaces are common in residential applications, but have had limited market adoption in commercial RTUs due to risks of condensate freezing, complications with proper condensate disposal, and increased fan consumption to overcome the higher static pressure loss from condensing heat exchanger. Several manufacturers offer condensing RTU and MUA products for cold-climate operation, where sufficiently long heating seasons or low temperatures provide reasonable paybacks. GTI recently outlining key R&D needs for further market adoption: decreasing the pressure drop for the condensing heat exchanger to below 0.15" wg, increasing usage of staged fans for RTUs, and decreasing RTU furnace oversizing.[264]	
Unit Energy Savings	10%	Estimated savings of condensing systems with >90% thermal efficiency
Technical Energy Savings Potential	109 TBtu	Gas furnace heating

[262] (a) Taco. 2015. "Zone Sentry Zone Valve." August 2015. Available at: http://www.taco-hvac.com/uploads/FileLibrary/100-82.pdf
(b) GSA. 2017. "Intelligent Energy Valves for Hydronic Systems System." GSA Green Proving Ground. August 2017. Available at: https://www.gsa.gov/portal/getMediaData?mediaId=251335
[263] Guernsey et al. 2015. "Pump and Fan Technology Characterization and R&D Assessment." Navigant Consulting Inc. Prepared for DOE BTO. October 2015. Available at: https://energy.gov/sites/prod/files/2015/10/f27/bto_pumpfan_report_oct2015.pdf
[264] Kosar, Douglas. 2014. "High-Efficiency Heating Rooftop Units (RTUs) – The Final Frontier for Condensing Gas Furnaces." GTI. CenterPoint Energy Energy Efficiency and Technology Conference. May 2014. Available at: http://www.gastechnology.org/Expertise/Documents/ETP/ETP-CenterPoint-Energy-Conference-Condensing-RTU-Presentation-05-21-2014.pdf

Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.90	2	1	2	2	3

C.35 Thermosyphon Cooling Tower

Technology Description	Johnson Controls developed a hybrid heat rejection system for water-cooled chillers that reduces the amount of water required by conventional evaporative cooling towers. The system involves a first stage where the entering water rejects heat to a closed-loop air-cooled thermosyphon system, followed by a conventional evaporative cooling tower stage. Johnson Controls estimates the two-stage system reduces water consumption by 49% with an increased energy consumption of 15%. The technology is designed for large chiller systems like data centers, as well as power plants and manufacturing facilities looking to decrease their water consumption and operating costs.[265]	
Unit Energy Savings	0%	Technology is primarily a water saving measure
Technical Energy Savings Potential	N/A	

Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.75	1	2	2	4	1

C.36 Heat-Recovery RTU for Water Pre-Heating

Technology Description	Rheem has developed a RTU system that can switch between using a standard air-cooled condenser and a water-cooled condenser that can pre-heat water for domestic hot water in the building. In a California field study, the technology reduced hot water consumption by more than 35% and increased space cooling efficiency when operating with the water-cooled condenser.[266]	
Unit Energy Savings	5%	Estimated increased space cooling efficiency, primarily provides water heating energy savings
Technical Energy Savings Potential	2 TBtu	All RTU cooling energy consumption in restaurants, higher savings for water heating energy consumption

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[265] (a) JCI. 2016. "Johnson Controls BlueStream Hybrid Cooling Systems." Johnson Controls. 2016. Available at: http://www.johnsoncontrols.com/-/media/jci/be/united-states/blue-stream-hybrid-cooling-systems/be_brochure_bluestream_chillers_web_140400sg2.pdf
(b) Carter et al. 2017. "Thermosyphon Cooler Hybrid System for Water Savings in an Energy-Efficient HPC Data Center: Modeling and Installation." NREL Presented at the 2017 ASHRAE Winter Conference. February 2017. Available at: https://www.nrel.gov/esif/assets/pdfs/66690.pdf

[266] Vandal, Hillary. 2016. "Waste Heat Recovery RTU and Hot Water System Field Installation Report." GTI. March 2016. Available at: http://www.etcc-ca.com/reports/waste-heat-recovery-rtu-and-hot-water-system-field-installation-report

Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.70	1	1	2	4	3

C.5 Full Commercialization

The following section includes descriptions for commercialized technologies that had lower scores than those in Appendix B.

C.37 Unitary Fault Detection and Diagnostic System

Technology Description	Proper performance and efficiency of commercial HVAC systems involves the coordinated operation of various sensors, motors, dampers, and other subsystems. HVAC system performance often deviates from design performance due to system malfunctions, equipment wear, manual controls overrides, and other causes. These faults often begin with little or no noticeable change in system performance or operation, but over time can lead to decreased capacity, efficiency, comfort, reliability, and longevity. Studies have shown that even a collection of relatively small faults can reduce RTU efficiency by 15%, and several moderately severe faults reduce efficiency by 26%. Manufacturers and vendors have developed fault detection and diagnostics systems for RTUs and other HVAC equipment that provide greater insight into the system's performance and identification of faults when they occur. FDD systems provide energy savings and other comfort and operational benefits by increasing the likelihood and restorative impact of system maintenance. Products are available for RTUs, AHUs, and other systems as both factory-installed and field-retrofit options.[267]	
Unit Energy Savings	15%	Estimated savings from field studies
Technical Energy Savings Potential	111 TBtu	RTU cooling energy consumption
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)	

Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
2.35	2	2	3	3	3

[267] (a) Cherniack, Mark. 2013. "Rooftop Units Fault Detection and Diagnostics – Part of the Evidence-based Design and Operations PIER Program." New Buildings Institute. Prepared for CEC. March 2013. Available at: https://newbuildings.org/wp-content/uploads/2015/11/RooftopUnitsFDD_FinalResearchSummary1.pdf
(b) Southern California Edison. "Evaluating the Effects of Common Faults on a Commercial Packaged Rooftop Unit." ET13SCE7050. July 2015. Available at: http://www.etcc-ca.com/reports/evaluating-effects-common-faults-commercial-packaged-rooftop-unit?dl=1461105088.

C.38 Baopt Pulse Cooling Control

Technology Description	For European and other global markets, Bosch has developed a ventilation control system that creates more even temperature distribution with lower energy consumption. Originally known as Baopt Pulse Cooling, Bosch's Climotion system uses a series of dampers, fan controllers, and in-room sensors to more accurately measure room conditions and adjust the airflow rate of both supply and return air systems. The system uses slower airflow rates decreasing fan energy consumption. The technology has a number of case studies in Europe and other global markets, but not in North America.[268]				
Unit Energy Savings	10%	Conservative estimates based on field studies in Europe			
Technical Energy Savings Potential	200 TBtu	Based on HVAC pump energy consumption from 2015 BTO Pumps and Fans Report[269]			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.35	2	2	3	3	3

C.39 Nanofiber Air Filter

Technology Description	HVAC systems use filters to remove dust, pollen, and other contaminants from the supply air stream to maintain IAQ and system performance. Several manufacturers have developed high-performance filters using specialized designs and materials, including nanofibers, that have lower associated fan energy consumption by minimizing pressure drop across the filter, especially over time as filters accumulate dust. DOD ESTCP is currently conducting a demonstration of a nano-enabled air filter and projects up to 8% HVAC system energy savings compared to standard filters.[270]				
Unit Energy Savings	8%	Estimated from vendor literature			
Technical Energy Savings Potential	160 TBtu	Based on HVAC pump energy consumption from 2015 BTO Pumps and Fans Report[271]			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction

[268] DEOS Controls Website. Accessed August 2017. Available at: https://www.deos-controls.com/solutions/climotion/
Bosch. 2015. "Climotion Ensures a Better Climate." Bosch Energy and Building Solutions. July 2015. Available at: http://www.bosch-energy.de/media/standardpages/news/broschueren/Bosch-Broschuere-BAOPT_en.pdf
[269] Guernsey et al. 2015. "Pump and Fan Technology Characterization and R&D Assessment." Navigant Consulting Inc. Prepared for DOE BTO. October 2015. Available at: https://energy.gov/sites/prod/files/2015/10/f27/bto_pumpfan_report_oct2015.pdf
[270] Doshi, Jayesh. 2017. "Nanofiber-based Low Energy Consuming HVAC Air Filters." ESTCP. 2017. Available at: https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Conservation-and-Efficiency/EW-201724
Camfil Website. Accessed August 2017. Available at: http://www.camfil.us/Filter-Technology/Energy-Savings/
[271] Guernsey et al. 2015. "Pump and Fan Technology Characterization and R&D Assessment." Navigant Consulting Inc. Prepared for DOE BTO. October 2015. Available at: https://energy.gov/sites/prod/files/2015/10/f27/bto_pumpfan_report_oct2015.pdf

2.20	2	2	3	2	3

C.40 Mixed-Mode Conditioning

Technology Description	Mixed-mode conditioning refers to a hybrid approach to space conditioning and ventilation for commercial buildings that combine natural ventilation from operable windows and mechanical systems. Case studies have shown 20% or greater energy savings for mild climates. Limitations for the technology exist for non-ideal climates, poor outdoor air quality, or noisy areas.[272]	
Unit Energy Savings	20%	Estimate based on field studies
Technical Energy Savings Potential	103 TBtu	All commercial cooling in climate zone 4
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)	

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.20	2	2	2	3	3

C.41 Engine-Driven Heat Pump

Technology Description	In place of an electrically driven compressor, engine-driven heat pumps use a gas-fired engine to drive the compressor of a vapor-compression heat pump. The technology is commercially available for RTU, VRF, and other commercial equipment types in places where peak demand and electricity costs are significantly higher than natural gas prices. Manufacturers include Aisin, Yanmar, Intellichoice, and several others. Engine-driven heat pumps offer COPs up to 1.4 for heating when factoring in waste heat recovery, and cooling COPs of 1.0-1.3. On a seasonal basis, the technology offers an estimated 20-40% primary energy savings, but is primarily installed for utility cost concerns. Researchers are also looking at variants using organic Rankine cycles and other engine technologies.[273]	
Unit Energy Savings	20%	Estimate based on full year primary energy savings, will vary by location and climate zone
Technical Energy Savings Potential	168 TBtu	RTU cooling and heat pump heating energy consumption
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)	

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction

[272] Walker, Andy, 2016. "Natural Ventilation." NREL. Whole Building Design Guide. August 2016. Available at: https://www.wbdg.org/resources/natural-ventilation

[273] (a) IntelliChoice Website. Accessed August 2017. Available at: http://iceghp.com/commercial-hvac-system/
(b) Yanmar Website. Accessed August 2017. Available at: http://www.yanmarenergysystems.eu/Products/
(c) Mounier and Schiffmann. 2017. "ORC Driven Heat Pump Running on Gas Bearings for Domestic Applications: Proof of Concept and Thermo-Economic Improvement Potential." May 2017. Available at: http://hpc2017.org/wp-content/uploads/2017/06/O.3.6.1-ORC-driven-Heat-Pump-based-on-gas-supported-turbomachinery-for-domestic.pdf

2.15	2	2	2	2	5

C.42 Solar Thermal Cooling System

Technology Description	Thermally activated heat pumps such as absorption and adsorption systems have the possibility of using solar thermal or waste heat for additional primary energy savings. Several manufacturers offer solar thermal panels packaged with their heat pump systems, or provide specifying information for the correct temperatures and flow-rates for a built-up system. Depending on the application, climate, etc., heat pumps using solar thermal energy can save 80% or more in primary energy savings with substantially lower utility costs. These systems are limited for niche applications due to high cost, complexity, and space requirements, as well as the need for backup systems for nighttime usage. [274] Solar thermal systems can also provide space heating through solar ventilation preheating and a number of thermally activated heat pump cycles (e.g., absorption, adsorption, liquid desiccant).	
Unit Energy Savings	50%	Conservative estimate, savings will depend on the heating source
Technical Energy Savings Potential	218 TBtu	Chiller energy consumption
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)	

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.15	2	1	1	4	5

C.43 UV Light Treatment

Technology Description	Ultraviolet (UV) lights placed within ducted HVAC system can destroy airborne biological contaminants that can build up on filters, heat exchangers, and other surfaces. By reducing contaminant build up on heat exchangers, the HVAC system maintains high efficiency and IAQ. Vendors project system energy savings of 10-35% by minimizing heat exchanger fouling. The lights consume electricity, so any performance benefit must offset the light's energy consumption.[275]	
Unit Energy Savings	5%	Estimate based on vendor projections
Technical Energy Savings Potential	74 TBtu	All vapor-compression cooling energy consumption
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)	

[274] (a) FIZ Karlsruhe. 2016. "Cooling with Solar Heat." BINE Information Service. September 2016. Available at: http://www.bine.info/fileadmin/content/Publikationen/Themen-Infos/III_2016/Englische_Dateien/themen_0316_engl_internetx.pdf
(b) Ruschenburg et al. 2013. "A Review of Market-Available Solar Thermal Heat Pump Systems." IEA SHC Task 44 / HPP Annex 38. March 2013. Available at: http://task44.iea-shc.org/data/sites/1/publications/T44A38-SubA-Report1-1305031.pdf

[275] Fencl, Forrest. 2014. "UV-C Light Benefits in HVAC Applications." ACHRNews. January 2014. Available at: http://www.achrnews.com/articles/125256-uv-c-light-benefits-in-hvac-applications

Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.15	1	2	4	4	3

C.44 Occupant Comfort Feedback Control

Technology Description	The software vendor Comfy uses aggregated temperature preferences and direct feedback from building occupants to more closely control comfort in individual zones and workstations. By tuning each zone to demand, the system more precisely controls the amount of space conditioning reaching each zone, reducing hot and cold areas, and providing better zone-by-zone setback during unoccupied hours. Combined, the software saves an estimated 15-25% on office HVAC energy consumption, with GSA GPG demo showing 20% cooling and 47% heating savings. The company primarily markets the technology for improved comfort, operational savings, tenant retention, and other non-energy benefits.[276]				
Unit Energy Savings	15%	Conservative estimate based on field studies			
Technical Energy Savings Potential	71 TBtu	HVAC energy consumption for large offices			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.00	1	2	4	3	3

C.45 Advanced Chiller Control Valve

Technology Description	A specialized chilled water control valve that monitors the flowrate and temperatures for supply and return pipes, and adjusts the flowrate to maintain proper differential temperature (i.e., delta T). The valve operates in addition to the standard building management system to more precisely maintain chiller water temperature differential, which improves chilled water system capacity and efficiency.[277]	
Unit Energy Savings	20%	Estimate based on vendor literature
Technical Energy Savings Potential	87 TBtu	All chiller-type commercial cooling systems

[276] Comfy Website. Accessed August 2017. Available at: https://www.comfyapp.com/?home
GSA. 2015. "Socially Driven HVAC Optimization." December 2015. Available at: https://www.gsa.gov/portal/content/121082

[277] (a) Rybka, Bob. 2014. "Knowledge is Power Belimo Energy Valve – CHW Delta T Mitigation Study." Belimo. 2014. Available at: http://www.bcxa.org/wp-content/uploads/2014/06/Belimo-Combined.pdf
(b) Belimo. 2012. "Knowledge is Power – Belimo Energy Valve." Control Trends. 2012. Available at: http://controltrends.org/wp-content/uploads/2012/04/Energy-Overview-Energy-valve.pdf

Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.00	1	2	4	3	3

C.46 Chiller with Water Refrigerant

Technology Description	The companies Efficient Energy and Kawasaki have developed centrifugal chillers that use liquid water (R-718) as the refrigerant. The Efficient Energy eChiller has a capacity of 35 kW (10 ton) and is primarily aimed at industrial, data center, and other non-building A/C applications, due to limitations with temperature range (60°F lowest operating point). At this temperature, COP will be 3.7 at 95°F OAT, which is lower than other chiller systems.[278] The Kawasaki model is a 100-ton chiller capable of the full performance envelope of conventional chillers at similar COPs. The technology is primarily positioned as zero-GWP alternatives conventional HVAC systems, rather than as an energy saving technology.[279]				
Unit Energy Savings	0-5%	No energy savings based on current performance, projected to have some savings if developed			
Technical Energy Savings Potential	22 TBtu	All chiller-type commercial cooling systems			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.00	1	2	3	4	3

C.47 Brayton Heat Pump

Technology Description	Brayton heat pumps use an electrically driven turbocompressor to compress and then expand a gaseous working fluid, typically air, to operate a heat pump cycle. The technology is commonly used for transportation comfort systems, but limited adoption for buildings. The Ukrainian manufacturer UPEC developed a Brayton-cycle turbocompressor HVAC system that offers 2.0-4.5 COP performance in heating mode (3.75 COP at rating condition) and 1.3-1.7 COP for cooling (1.5 COP at rating condition). In addition, the unit can provide outside air and heat recovery for water heating.[280]	
Unit Energy Savings	15%	15% energy savings for space heating over electric heat pumps (3.75 vs. 3.20), negative savings for space cooling
Technical Energy Savings Potential	14 TBtu	Heat pump heating energy consumption

[278] Efficient Energy Website. Accessed 2017. Available at: https://efficient-energy.com/en/the-most-efficient-chiller/sustainable-refrigeration-technology/
[279] Sakamoto, Hayato. 2015. “Kawasaki turbo chiller using water as a refrigerant.” Kawasaki. ATMOsphere Asia. February 2015. Available at: http://www.atmo.org/presentations/files/ATMO_Asia_2015_8_IR_5_Hayato_Sakamoto.pdf
[280] UPEC Air-Cycle Turbo Technology Systems Website. Accessed August 2017. Available at: http://www.att.upec.ua/en/

Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
2.00	1	2	3	4	3

C.48 Synchronous and Notched Fan Belts

Technology Description	A variety of commercial HVAC fans use belts to connect the motor to the fan. Implementing synchronous or notched fan belts could yield 2-5% fan energy savings relative to a standard V-shaped fan belt. Notched fan belts have grooves running perpendicular to the length of the belt, which reduce its bending resistance during operation. Synchronous fan belts have 'teeth' that fit into grooves on the pulley that rotates the belt.[281]				
Unit Energy Savings	3.5%	Estimate based on vendor savings estimates			
Technical Energy Savings Potential	70 TBtu	Based on HVAC pump energy consumption from 2015 BTO Pumps and Fans Report[282]			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	Technical Energy Savings	Upfront Cost	Operational Complexity	Non-Energy Benefits	Peak Demand Reduction
1.85	1	3	3	2	3

C.49 Evaporative Condenser

Technology Description	Commercial RTUs are designed for reliable operation in a variety of climate regions, but can be enhanced for hot-dry climates through the use of evaporative cooling stages and other technologies. Demonstrated for several California utilities and the Western Cooling Efficiency Center (WCEC), the factory-installed or retrofit RTUs with evaporative pre-cooling technologies can reduce energy consumption by 15% and greater, with significant peak demand savings. The technology uses an evaporative cooling stage for both condenser and inlet air, which decreases the required temperature lift of the conventional processes. The technologies do increase on-site water consumption and require additional maintenance.[283]

[281] (a) DOE. 2012. "Replace V-Belts with Notched or Synchronous Belt Drives." Advanced Manufacturing Office. November 2012. Available at: https://energy.gov/sites/prod/files/2014/04/f15/replace_vbelts_motor_systemts5.pdf
(b) GSA. 2014. "Synchronous and Cogged Fan Belts." GSA Green Proving Ground. March 2014. Available at: https://www.gsa.gov/portal/content/188023
[282] Guernsey et al. 2015. "Pump and Fan Technology Characterization and R&D Assessment." Navigant Consulting Inc. Prepared for DOE BTO. October 2015. Available at: https://energy.gov/sites/prod/files/2015/10/f27/bto_pumpfan_report_oct2015.pdf
[283] (a) Woolley, Jonathan. 2015. "Field Results: Dual-Evaporative Pre-Cooling Retrofit." WCEC. January 2015. Available at: http://wcec.ucdavis.edu/wp-content/uploads/2015/02/Case-Study-Palmdale_Revised_02112015.pdf
(b) Woolley, Jonathan. 2016. "Outside of the Box: Climate Appropriate Hybrid Air Conditioning as a Paradigm Shift for Commercial Rooftop Packaged Units." 2016 ACEEE Summer Study on Energy Efficiency in Buildings. August 2016, Available at: http://aceee.org/files/proceedings/2016/data/papers/3_124.pdf

Unit Energy Savings	15%	Estimate based on field studies, savings will vary by climate and operating hours			
Technical Energy Savings Potential	137 TBtu	Energy consumption for RTU cooling and VAV ventilation systems for climate zones 1-4			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.85	2	1	2	1	5

C.50 Demand Controlled Kitchen Ventilation

Technology Description	Demand Control Kitchen Ventilation (DCKV) is a method of modulating the speed of the exhaust fan for commercial kitchen ventilation depending on cooking activities. Kitchen ventilation systems remove the heat and effluent gasses generated by the cooking process from the kitchen space, ensuring the comfort and safety of the cooking staff, and preventing cooking odors from spreading beyond the kitchen. Traditionally, commercial kitchen ventilation systems operate at their maximum designed speed and volume throughout the duration of a kitchen's operating hours or provide manual control typically for two exhaust fan speeds. DCKV provides automatic, continuous control over fan speed in response to temperature, optical, or infrared sensors that monitor cooking activity or directly communicate with cooking appliances.[284]				
Unit Energy Savings	30%	Conservative estimate based on 30-70% range of energy savings			
Technical Energy Savings Potential	56 TBtu	HVAC energy consumption for food service buildings			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.70	1	2	3	2	3

[284] (a) Keyes et al. 2016. "Demand Control Kitchen Ventilation." Big Ten and Friends Conference. 2016. Available at: https://www.fs.illinois.edu/docs/default-source/Big-10-and-Friends/2016-presentations/demandcontrolledventilationforcommercialkitchen.pdf?sfvrsn=2
(b) EPA. 2014. "Technology Profile: Demand Control Kitchen Ventilation (DCKV)." ENERGY STAR. August 2014. Available at: https://www.energystar.gov/sites/default/files/dckv_technology_profile.pdf

C.51 Solar PV Cooling System

Technology Description	Increasingly commercial buildings are installing solar photovoltaic (PV) panels to operate on-site electric loads and exporting excess electricity to the local grid. Several manufacturers have developed RTU and ductless mini-split products that use a series of solar PV panels with microinverters connect directly with the HVAC system before connecting with the building's main electrical panel.[285] DOD ESTCP program is currently demonstrating a RTU with direct current (DC)powered fans and compressors that will use energy directly from a rooftop panel array, and expects savings of 5-7% by eliminating power conversions.[286]				
Unit Energy Savings	5%	Estimated savings from eliminating AC/DC conversions			
Technical Energy Savings Potential	42 TBtu	RTU cooling and heat pump heating energy consumption			
Technology Readiness Level (TRL)	Late Stage Development (TRL 7-8)				
Final Score	**Technical Energy Savings**	**Upfront Cost**	**Operational Complexity**	**Non-Energy Benefits**	**Peak Demand Reduction**
1.35	1	1	1	2	5

[285] Lennox SunSource Commercial Energy System Website. Accessed August 2017. Available at: http://www.lennoxcommercial.com/products/solar-ready/sunsource

[286] Saussele, John. 2017. "Develop and Integrate a DC HVAC System to an Existing DC Microgrid DoD Installation." ESTCP. 2017. Available at: https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Conservation-and-Efficiency/EW-201725

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