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Building Technologies Office

Energy Savings Potential and Research, Development, & Demonstration Opportunities for Residential Building Heating, Ventilation, and Air Conditioning Systems

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NOTICE

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

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List of Acronyms

ABHX	Air-Beating Heat Exchanger
A/C or AC	Air Conditioning or Air Conditioner
ACEEE	American Council for an Energy-Efficient Economy
ACHR	Air-Conditioning, Heating, and Refrigeration
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AMP	Active Modular Phytoremediation
ARPA-E	Advanced Research Projects Agency - Energy
ARTI	Air-Conditioning and Refrigeration Technology Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASPE	American Society of Plumbing Engineers
BAIHP	Building America Industrialized Housing Partnership
BEETIT	Building Energy Efficiency through Innovative Thermodevices
BFE	Binary-Fluid Ejector
BLDC	Brushless Direct Current
BTP	U.S. Department of Energy, Building Technologies
Btu	British thermal unit
Btuh	British thermal unit hour
CASE	Center for Architecture, Science and Ecology
CAV	Constant Air Volume
CBEA	Commercial Building Energy Alliance
CEC	California Energy Commission
CO_2	Carbon Dioxide
COP	Coefficient of Performance
DCV	Demand-Controlled Ventilation
DEVap A/C	Desiccant-Assisted Evaporative Air Conditioner
DMS	Ductless Multi-Split
DOAS	Dedicated Outdoor Air System
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
DTU	Technical University of Denmark
DX	Direct-Expansion
eCOP	Effective Coefficient of Performance
EE&T	Energy Efficiency and Technology
EERE	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
EIA	U.S. Department of Energy, Energy Information Administration
EMS	Energy Management System
EPA	U.S. Environmental Protection Agency
ERV	Energy Recovery Ventilator
ES	Executive Summary

FDD	Fault Detection and Diagnostics
FEMP	Federal Energy Management Program
ft	Foot
GAHP	Gas-Fired Absorption Heat Pump
GAX	Generator-Absorber Heat Exchange
GE	General Electric
GEHP	Gas-Engine-Driven Heat Pump
GHP	Geothermal Heat Pump
GWP	Global-Warming Potential
HCFC	Hydrochlorofluorocarbon
HDAC	Hot-Dry Air Conditioner
HFC	Hydrofluorocarbon
HRV	Heat Recovery Ventilator
HSPF	Heating Seasonal Performance Factor
HT	Heat Transfer
HVAC	Heating, Ventilation, and Air Conditioning
HX	Heat Exchanger
IAQ	Indoor Air Quality
IDEC	Indirect/Direct Evaporative Cooler
IEA	International Energy Agency
IHP	Integrated Heat Pump
IIR	International Institute for Refrigeration
ITC	Isothermal Turbocompressor
JARN	Japanese Air-Conditioning, Heating, and Refrigeration News
LBNL	Lawrence Berkeley National Laboratory
LDAC	Liquid-Desiccant Air Conditioner
mCHP	Micro-Combined Heat and Power
MCHX	Microchannel Heat Exchanger
NEEA	Northwest Energy Efficiency Alliance
NEH	Net Zero Energy Home
NIST	National Institute of Standards and Technology
NiTi	Nitinol
NSRC	Night Sky Radiant Cooling
NYSERDA	New York State Energy Research and Development Authority
OA	Outdoor Air
ODP	Ozone Depletion Potential
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PATH	Partnership for Advanced Technology in Housing
PCT	Patent Cooperation Treaty
PIER	Public Interest Energy Research
PNNL	Pacific Northwest National Laboratory
PSAC II	Public Safety Answering Center II

PUMF	Public Use Microdata File
Quad	Quadrillion Btu
R&D	Research and Development
RCx	Retrocommissioning
RD&D	Research, Development, and Demonstration
RECS	Residential Energy Consumption Survey
rpm	Revolutions per Minute
RTU	Rooftop Unit
SEDS	State Energy Data System
SEER	Seasonal Energy Efficiency Ratio
SMA	Smart-Memory Alloys
sq. ft.	Square Foot
SR	Switched-Reluctance
SWEEP	Southwest Energy Efficiency Program
TCCE	Turbo-Compressor-Condenser-Expander
TE	Thermoelectric
TES	Thermal Energy Storage
TIM	Thermal Interference Material
TSD	Technical Support Document
UMD	University of Maryland
US	United States
VOC	Volatile Organic Compounds
VRF	Variable Refrigerant Flow
VRV	Variable Refrigerant Volume
W	Watt
WCEC	Western Cooling Efficiency Center
ZT	Dimensionless figure of merit for thermoelectric materials

Executive Summary

The U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Building Technologies Program (BTP) commissioned this characterization and technology assessment of heating, ventilation, and air-conditioning (HVAC) systems for residential buildings. The main objectives of this study were the following:

- Identify a wide range of technology options in varying stages of technology development that could reduce residential HVAC energy consumption
- Prioritize and analyze selected technology options, including technical energy savings potential, applicability to various building or HVAC equipment types, non-energy benefits, and barriers to market adoption
- Recommend potential research, development, and demonstration (RD&D) initiatives that would support further development of the most promising technology options, based on technical energy savings potential, fit with DOE BTP's mission, and cost and complexity.

To develop the priority list of technology options and recommended RD&D initiatives for this study, we followed a technology selection, screening, and assessment process. We first generated a comprehensive list of 135 technology options (listed in Appendix A) from a variety of sources including: manufacturers' websites, industry publications, government organizations, university research, and industry experts. Through this initial screening, we cataloged general information about each technology such as its potential energy efficiency impact and potential applicability to various residential HVAC systems. After examining the initial list, we identified 52 technology options that demonstrated the highest potential to reduce HVAC energy consumption in residential buildings, but that have not yet been adopted widely by the market.

After our initial screen, we separated technology options for which there was a paucity of publicly available information, because they are still in the early stages of research and development (R&D). Because we were unable to find energy and cost savings estimates for these technology options, we identified 10 technology options that we could not evaluate against the other technology options. Thus, we did not prioritize them, but instead made separate recommendations for DOE, described in Section 5.4.1. Table ES-1 presents the 10 early-stage technology options that we identified.

Table ES-1. 10 Early-Stage Technology Options

Early-Stage Technology Options
Active Modular Phytoremediation Wall
Advanced Membrane Heat Pump
Air-Bearing Heat Exchanger
Bernoulli Heat Pump
Binary Fluid Ejector
Co-Fluid Vapor Compression
Metal-Foam Heat Exchanger
Self-Cleaning Heat Exchanger
Thermoelastic Cooling System
Turbo-Compressor-Condenser-Expander

We then conducted a preliminary analysis of each of the 42 remaining technology options (52 highest-potential less 10 early-stage) to better understand their technical energy savings potential for residential HVAC systems in the U.S. We determined the technical energy savings potential for each technology option by combining HVAC energy-use data from the *2010 Building Energy Data Book* (DOE 2011), the latest data from *2009 Residential Energy Consumption Survey* (EIA 2011), and unit energy savings estimates. For each technology option, this analysis expanded our understanding of: technical energy savings potential, installed costs, replacement potential, peak-demand reduction, other non-energy benefits, barriers to market adoption, and next steps for technology development.

Based on the preliminary analysis, we conducted another round of technology screening based on five criteria:

- Technical energy savings potential
- Fit with DOE BTP mission
- Cost/complexity
- Availability of non-energy benefits
- Potential for peak-demand reduction.

After scoring each technology option (based on the preliminary analyses and industry experts), we chose 19 priority technology options for the in-depth analysis. Each technology option shows strong potential to have one or more of the following impacts:

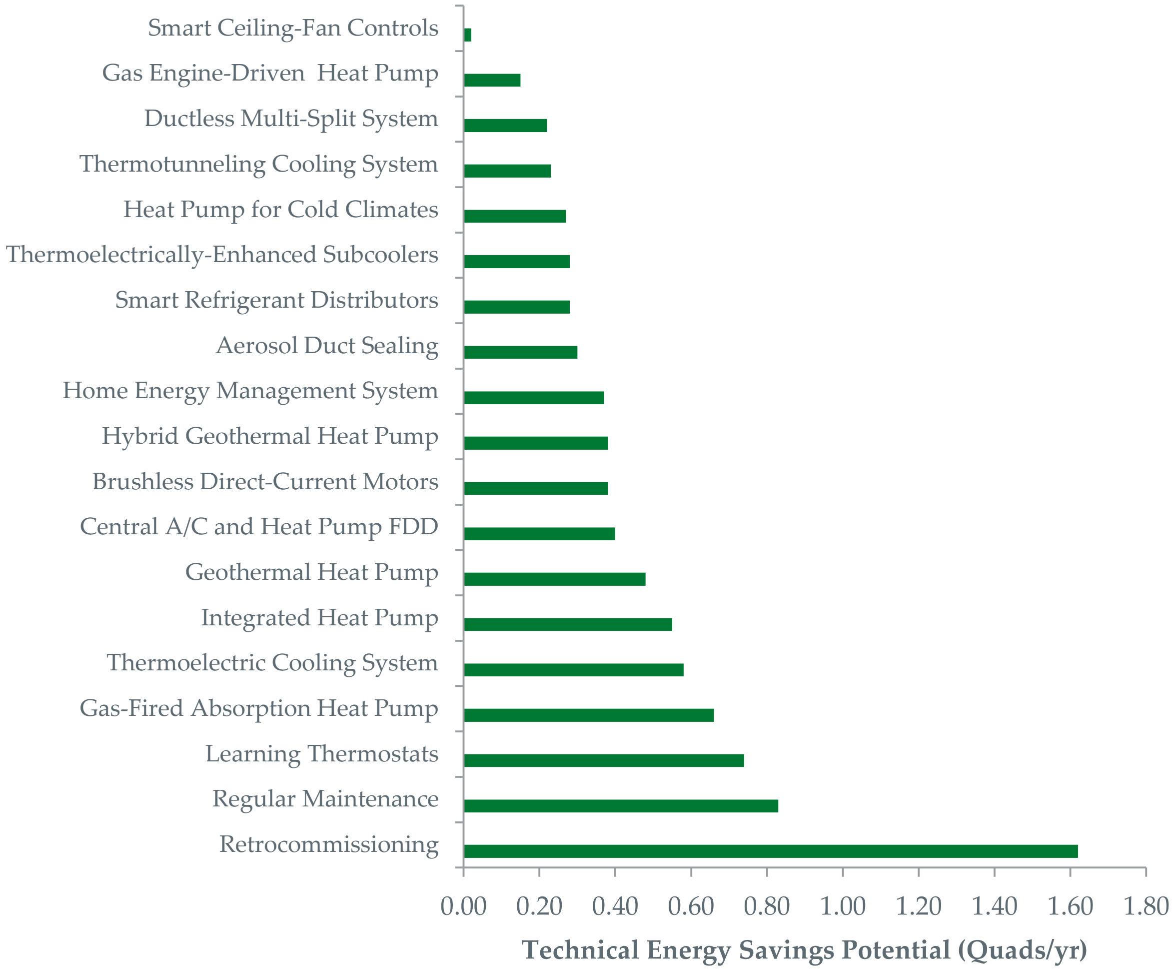
- Provides heating or cooling more efficiently using alternative refrigeration cycles, advanced heat-pump designs, or offsets the energy consumption of conventional systems by optimizing the performance of critical components
- Reduces common causes of poor performance and equipment degradation, improving system efficiency
- Utilizes monitoring and diagnostic tools to optimize and maintain the efficiency of residential HVAC systems over time, or employs innovative control strategies to reduce energy consumption without compromising occupant comfort.

Table ES-2 categorizes and presents the 19 priority technology options that we chose for the in-depth analysis.

Table ES-2. Summary of the Priority Technology Options

Recommended Initiatives	Applicable Technology Options
Advanced Component Technology Options	• Brushless Direct-Current Motors • Smart Refrigerant Distributors
Alternative Heating and Cooling Technology Options	• Gas-Fired Absorption Heat Pump • Thermoelectric Cooling System • Thermoelectrically Enhanced Subcoolers • Thermotunneling Cooling System
Advanced Heat-Pump Technology Options	• Ductless Multi-Split System • Gas-Engine-Driven Heat Pump • Geothermal Heat Pump • Heat Pump for Cold Climates • Hybrid Geothermal Heat Pump • Integrated Heat Pump
High-Performance System Design and Restoration Technology Options	• Aerosol Duct Sealing • Regular Maintenance • Retrocommissioning
Intelligent Controls and Diagnostic Technology Options	• Central A/C and Heat Pump Fault Detection and Diagnostics • Home Energy Management System • Learning Thermostat • Smart Ceiling-Fan Controls

Figure ES-1 presents the technical energy savings potential for the 19 priority technology options.



Note: Potential savings are not additive for most technology options and applications.

Figure ES-1. Technical Energy Savings Potential for the Priority Technology Options

Because technical energy savings potential depends both on the applicability of the technology across HVAC equipment/systems and the projected annual unit energy savings, technology options that address both heating and cooling (e.g., Integrated Heat Pump) or benefit multiple HVAC system types (e.g., Retrocommissioning) have larger technical energy savings potentials. Technology options that a) are readily retrofit into existing buildings either as a supplementary system (e.g., Learning Thermostat), or b) could be integrated in replacement equipment (e.g., Central A/C and Heat Pump Fault Detection and Diagnostics [FDD]), have higher technical energy savings potential as well.

DOE BTP commissioned a similar study in 2011to investigate energy-efficient technologies for commercial HVAC systems (Goetzler, et al. 2011). Although this residential study followed a screening and scoring process similar to the commercial report, we developed a different set of priority technology options for each study based primarily on the specific differences in the desired characteristics for residential and commercial HVAC systems in the U.S. Additionally, some of the priority technology options offer considerable energy savings for both residential and commercial HVAC systems.

Based on our review of the priority technology options selected for this residential study and the 2011 commercial study, we recommend that DOE and industry stakeholders lead the RD&D initiatives summarized in Table ES-3 through ES-7, respectively. Because the technology-development requirements for residential and commercial applications are often similar, we combined recommended residential and commercial RD&D initiatives, where appropriate.

Table ES-3. Summary of Recommended DOE-Lead Residential and Commercial HVAC Initiatives (R&D-Stage Technology Options)

Recommended Initiatives	Applicable Market(s)	Applicable Technology Options
Support development of advanced high-ZT materials and low work-function materials for solid-state cooling applications	Residential, Commercial	• Thermoelectric Cooling System • Thermoelectrically Enhanced Subcoolers • Thermotunneling Cooling System
Support development of designs reducing the use of rare-earth metals	Residential, Commercial	• Magnetic Cooling Cycle • Thermoelectric Cooling System • Thermoelectrically Enhanced Subcoolers • Thermotunneling Cooling System • Brushless Direct-Current Motors
Support the development of prototypes for laboratory testing in capacities suitable for HVAC systems	Residential, Commercial	• Metal-Foam Heat Exchangers • Thermoelectrically Enhanced Subcoolers • Thermotunneling Cooling System
Support development of improved manufacturing strategies for small-scale, advanced-material technology options	Residential	• Magnetic Cooling Cycle • Metal-Foam Heat Exchangers • Thermoelectric Cooling System • Thermoelectrically Enhanced Subcoolers • Thermotunneling Cooling System • Brushless Direct-Current Motors

Table ES-4. Summary of Recommended DOE-Lead Residential and Commercial HVAC Initiatives (Emerging and Commercially Available Technology Options)

Recommended Initiatives	Applicable Market(s)	Applicable Technology Options
Conduct long-term field studies on alternative ventilation strategies for both commercial and residential applications	Residential, Commercial	• Demand-Controlled Ventilation • Thermal Displacement Ventilation
Support development of strategies to facilitate assessment of airflow and thermal efficiency of ducts	Residential, Commercial	• Aerosol Duct Sealing • Duct-Leakage Diagnostics
Conduct independent laboratory and field testing of intelligent controls and diagnostic technology options	Residential, Commercial	• Central A/C and Heat Pump FDD • Home Energy Management System • Learning Thermostat • Smart Ceiling-Fan Controls • Smart Refrigerant Distributors
Support further refinement of the energy economics for performance optimization and diagnostics technology options	Residential, Commercial	• Building Energy Information System • Continuous Commissioning • Packaged Rooftop Unit FDD • Retrocommissioning • Home Energy Management System • Central A/C and Heat Pump FDD • Learning Thermostat • Regular Maintenance
Develop greater understanding of real-world energy performance for HVAC equipment and systems over their lifetime	Residential, Commercial	• Building Energy Information System • Continuous Commissioning • Packaged Rooftop Unit FDD • Retrocommissioning • Central A/C and Heat Pump FDD • Regular Maintenance
Conduct long-term field testing of alternative and advanced heat-pump designs for heating applications	Residential	• Gas-Fired Absorption Heat Pump • Gas Engine-Driven Heat Pump • Ductless Multi-Split System • Integrated Heat Pump • Heat Pump for Cold Climates
Develop cost-effective and reliable gas-fired heat-pump products for single-family residential applications	Residential	• Gas-Fired Absorption Heat Pump • Gas Engine-Driven Heat Pump
Develop novel strategies and equipment to reduce the upfront cost of geothermal heat pump systems	Residential	• Geothermal Heat Pump • Hybrid Geothermal Heat Pump • Integrated Heat Pump • Ductless Multi-Split System

Table ES-5. Summary of Recommended Manufacturer-Lead Residential and Commercial HVAC Initiatives

Recommended Initiatives	Applicable Market(s)	Applicable Technology Options
Develop techniques for cost-effective integration of technology options into replacement equipment and existing HVAC systems	Residential, Commercial	• Smart Refrigerant Distributors • Thermoelectrically Enhanced Subcoolers • Brushless Direct-Current Motors • Home Energy Management System • Learning Thermostat • Aerosol Duct Sealing
Conduct demonstrations of, and publish field data for, advanced components using a variety of equipment designs	Residential, Commercial	• Smart Refrigerant Distributors • Thermoelectrically Enhanced Subcoolers
Optimize the capabilities and number of sensors for performance optimization and diagnostics systems	Residential, Commercial	• Building Energy Information System • Continuous Commissioning • Packaged Rooftop Unit FDD • Retrocommissioning • Home Energy Management System • Central A/C and Heat Pump FDD • Learning Thermostat

Table ES-6. Summary of Recommended Industry-Organization-Lead Residential and Commercial HVAC Initiatives

Recommended Initiatives	Applicable Market(s)	Applicable Technology Options
Incorporate duct-leakage prevention and best practices into future building standards and codes	Residential, Commercial	• Aerosol Duct Sealing • Duct-Leakage Diagnostics
Develop improved test procedures and rating methods	Residential, Commercial	• Geothermal Heat Pump • Hybrid Geothermal Heat Pump • Integrated Heat Pump • Ductless Multi-Split System • Gas Engine-Driven Heat Pump • Heat Pump for Cold Climates
Increase collaboration among the various industry organizations to promote advanced equipment integrating HVAC and water-heating technology options	Residential, Commercial	• Integrated Heat Pump • Gas-Fired Absorption Heat Pump • Gas Engine-Driven Heat Pump
Establish industry standards for fault detection and diagnostics systems	Residential, Commercial	• Building Energy Information System • Continuous Commissioning • Packaged Rooftop Unit FDD • Central A/C and Heat Pump FDD

Table ES-7. Summary of Recommended Utility-Lead Residential and Commercial HVAC Initiatives

Recommended Initiatives	Applicable Market(s)	Applicable Technology Options
Offer incentives to decrease the upfront costs of performance optimization and diagnostics systems	Residential, Commercial	• Building Energy Information System • Continuous Commissioning • Packaged Rooftop Unit FDD • Retrocommissioning • Aerosol Duct Sealing • Regular Maintenance • Central A/C and Heat Pump FDD
Promote alternative and advanced heat-pump designs through commercialization and incentive programs	Residential, Commercial	• Heat Pump for Cold Climates • Geothermal Heat Pump • Ductless Multi-Split System

1 Introduction

The U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy (EERE), Building Technologies Program (BTP) commissioned this characterization and technology assessment of heating, ventilation, and air-conditioning (HVAC) systems for residential buildings. The main objectives of this study were the following:

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- Recommend potential research, development, and demonstration (RD&D) initiatives that would support further development of the most promising technology options, based on technical energy savings potential, fit with DOE BTP's mission, and cost and complexity.

1.1 Report Organization

Table 1-1 shows the organization of this report.

Table 1-1. Report Organization

Section	Content/Purpose
Executive Summary	Top-level summary
1	Introduction
2	Technology Selection and Screening Processes
3	Summary of the 19 Priority Technology Options
4	Summary of the 10 Early-Stage Technology Options
5	Conclusions
References	References
Appendix A	List of the Initial 135 Technology Options
Appendix B	List of Resources Used in Literature Search
Appendix C	Abridged Analyses of the 10 Early-Stage Technology Options
Appendix D	Preliminary Analyses
Appendix E	Technical Energy Savings Potential of the 42 Technology Options
Appendix F	Scoring Results for 42 Technology Options
Appendix G	In-Depth Analyses of the 19 Priority Technology Options

1.2 Background

In 2002 and 2011, DOE BTP commissioned studies to identify and analyze a wide range of technology options having the potential to reduce HVAC energy consumption in U.S. commercial buildings (Roth et al. 2002); Goetzler et al. (2011). We identified no previous study, however, that evaluated technology options to reduce energy consumption in U.S. residential buildings. The key differences of residential HVAC (compared to commercial HVAC) include:

- Equipment cooling and heating capacities are significantly lower.
- Space-heating efficiency is more important because space heating represents a larger portion of annual HVAC energy consumption.

- Historically, there has been less emphasis on controlled ventilation, although this is changing rapidly as building codes require tighter home construction and occupants become more aware of indoor air quality (IAQ) issues.
- Vapor-compression heat pumps are more widely used.
- The building occupant, particularly for single-family housing, is typically the building owner and, therefore, typically responsible for both equipment purchases and monthly energy bills.

Additionally, the residential building market is changing as more homeowners recognize the value of energy efficiency, in the following ways:

- Various utility and government programs encourage the purchase of high-efficiency equipment and performance of system maintenance through incentive programs.
- Residential equipment manufacturers and installation contractors have successfully marketed HVAC equipment meeting high-performance standards, such as ENERGY STAR.
- An increasing number of utilities provide detailed information on their monthly bills to educate residential consumers about their energy consumption.
- Homeowners have become more connected to information technology, and are interested in monitoring and controlling the HVAC system from their phone or computer.

In light of these differences and trends, DOE/BTP determined that an investigation into energy-saving technologies for residential HVAC systems would likely reveal unique energy-saving opportunities.

1.2.1 Breakdown of Residential HVAC Energy Consumption

According to *2011 Building Energy Data Book* (BEDB) (DOE 2011), the U.S. residential-building sector consumed 22.05 quadrillion Btu (Quad) of primary energy in 2010.[1] Energy consumption associated with HVAC equipment (i.e., space heating, and space cooling) accounts for over 40% of the total residential energy consumption at 9.33 Quads (Figure 1-1).[2]

[1] Primary energy accounts for the losses in generation, transmission, and distribution. We only account for these losses for electricity, as the transmission and distribution losses for natural gas and other fossil fuels tend to be small. Primary energy does not account for the losses associated with extraction.

[2] According to the BEDB, SEDS Adjustment (energy attributable to the residential-building sector, but not directly to specific end uses) account for 0.60 Quads. For illustration purposes, we distributed the 0.60 Quads across all categories in proportion to energy consumption of each end use.

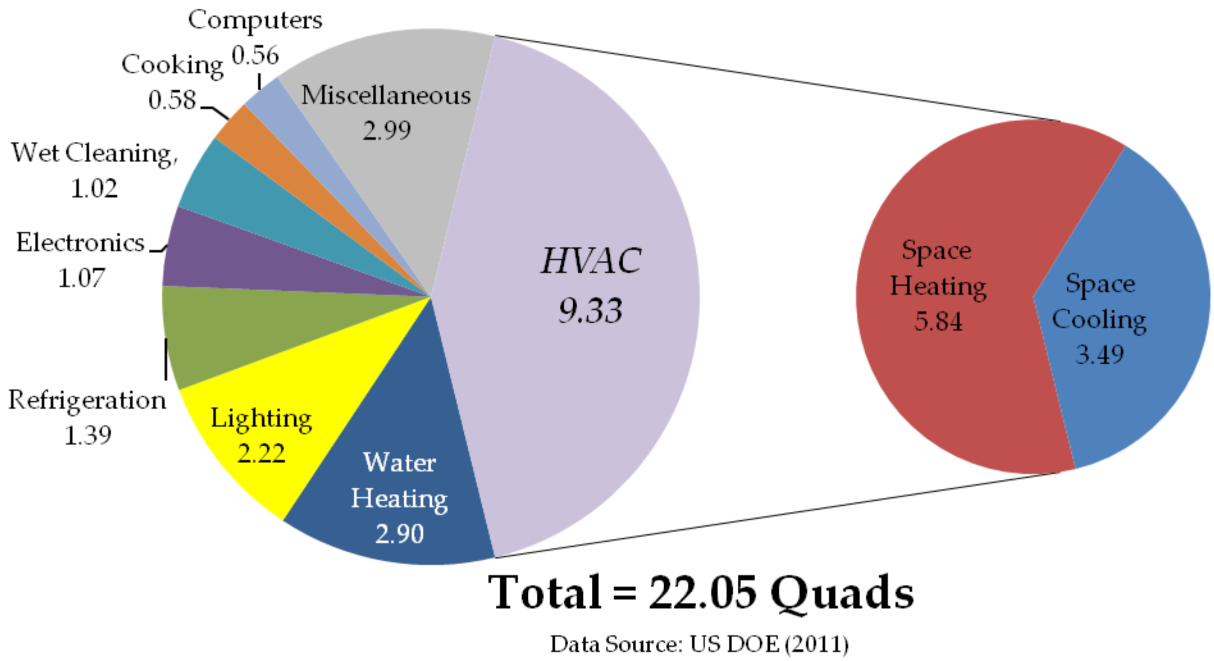


Figure 1-1. 2010 U.S. Residential-Building Sector Primary Energy Consumption (Quads)

Figure 1-2 presents the breakdown of residential HVAC energy consumption by fuel type.

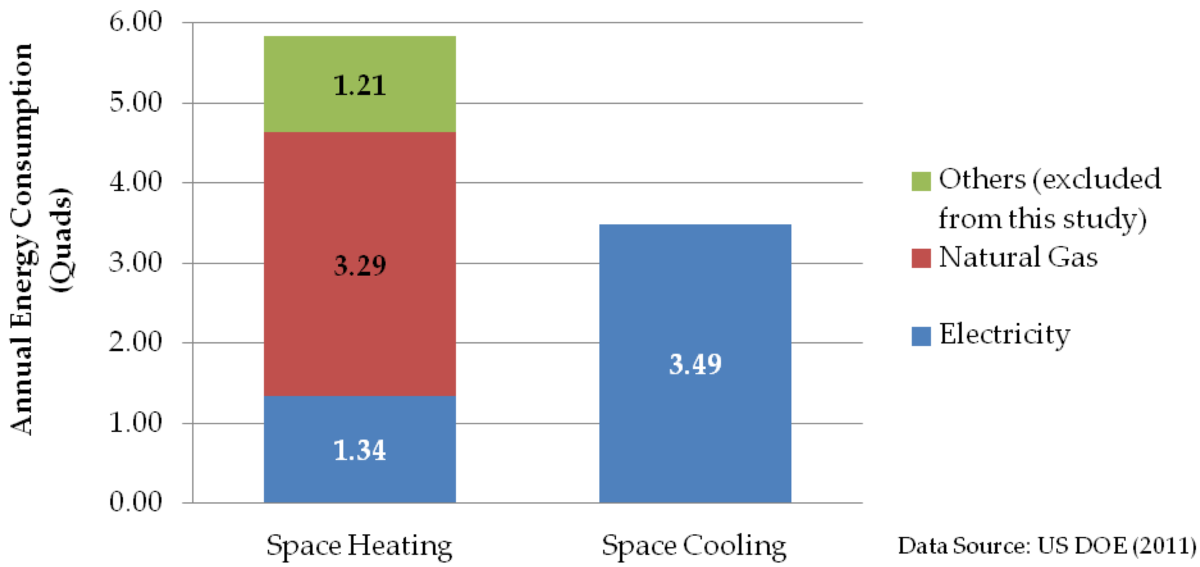


Figure 1-2. 2010 U.S. Residential-Building Sector HVAC Primary Energy Consumption, by Fuel Type

This study focuses on electricity and natural-gas consumption associated with HVAC equipment in the U.S. residential-building sector, which represents 87% percent of the total residential HVAC energy consumptions (8.12 of 9.33 Quads annually). Although fuel oil is somewhat common for space heating in the Northeast, its use nationally is low, and is decreasing (Northeast Gas Association 2010).

Because some technology options are only applicable to certain types of HVAC equipment, we broke down the HVAC energy consumption by equipment type to estimate technical energy savings potential[3] of candidate technology options. We based our estimated energy-consumption breakdown on the preliminary *2009 Residential Energy Consumption Survey* (RECS) Public Use Microdata File (PUMF) (EIA 2011). Because the 2009 RECS data were unavailable at the time of this report, we adapted data from 2005 RECS (EIA 2009).

Figure 1-3 and Figure 1-4 provide energy consumption for residential heating and cooling, respectively, by equipment type. We based all estimates of technical energy savings potential on these annual energy consumption estimates.[4]

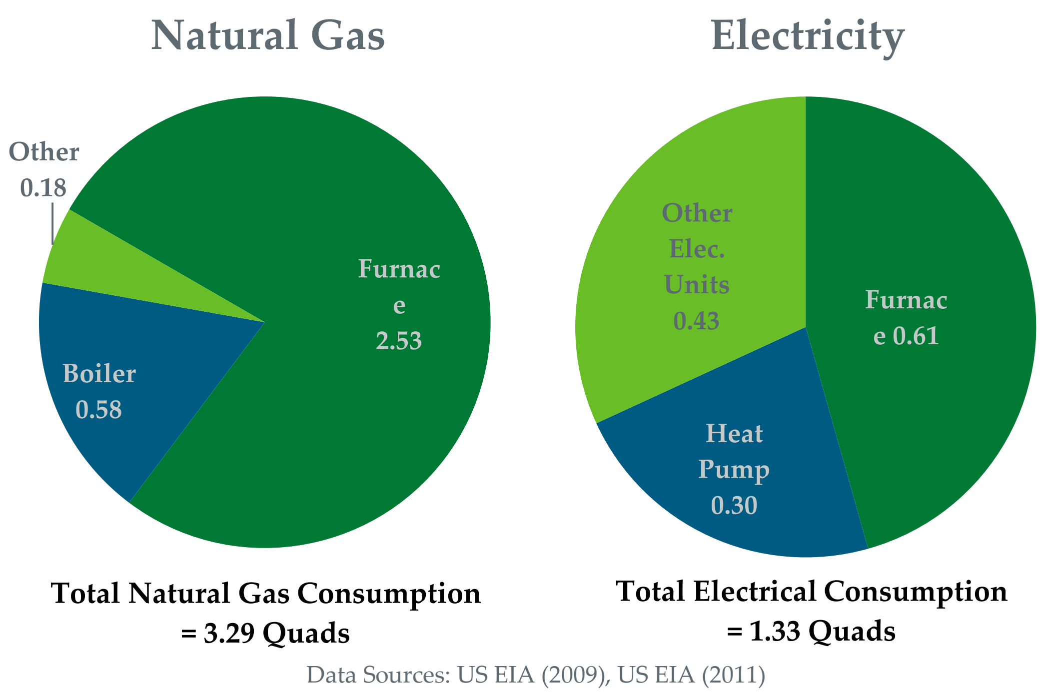


Figure 1-3. Percentage Breakdown of U.S. Residential-Building Energy Consumption for Space Heating (Quads)

[3] Technical energy savings potential is the theoretical national primary energy savings that could be achieved if all technically suitable installations are replaced with a particular energy-saving technology.
[4] For certain technologies, these energy consumption estimates are further broken down by climate zones, building size, or both, based on 2009 RECS data.

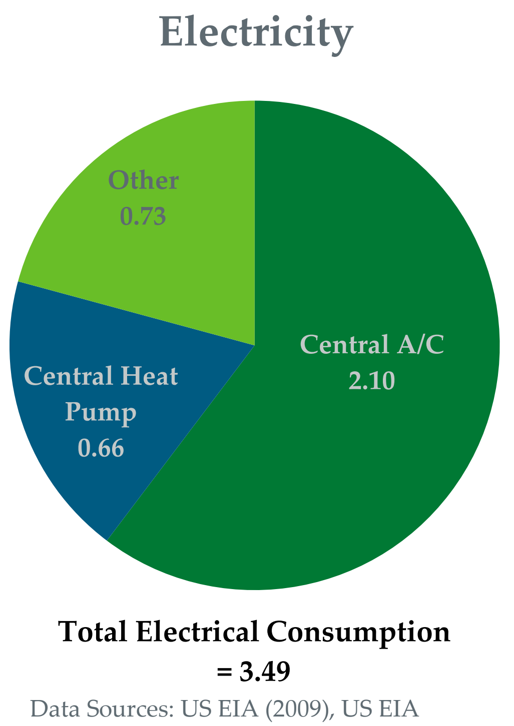


Figure 1-4. Percentage Breakdown of U.S. Residential-Building Energy Consumption for Space Cooling (Quads)

2 Technology Selection and Screening Processes

We examined a broad portfolio of technology options (135 options in total) that could reduce energy consumption of residential HVAC equipment. We then selected 52 of these technology options for further, more thorough evaluation. We filtered out 10 technology options that may have promise for residential HVAC applications, but for which we could not find adequate documentation to evaluate (early-stage technology options). Finally, we distilled the portfolio to 19 priority technology options for more in-depth analysis, including estimation of the technical energy savings potential and evaluation of the state of technology development. Figure 2-1 presents the overall flow of the technology selection, screening, and assessment processes we followed.

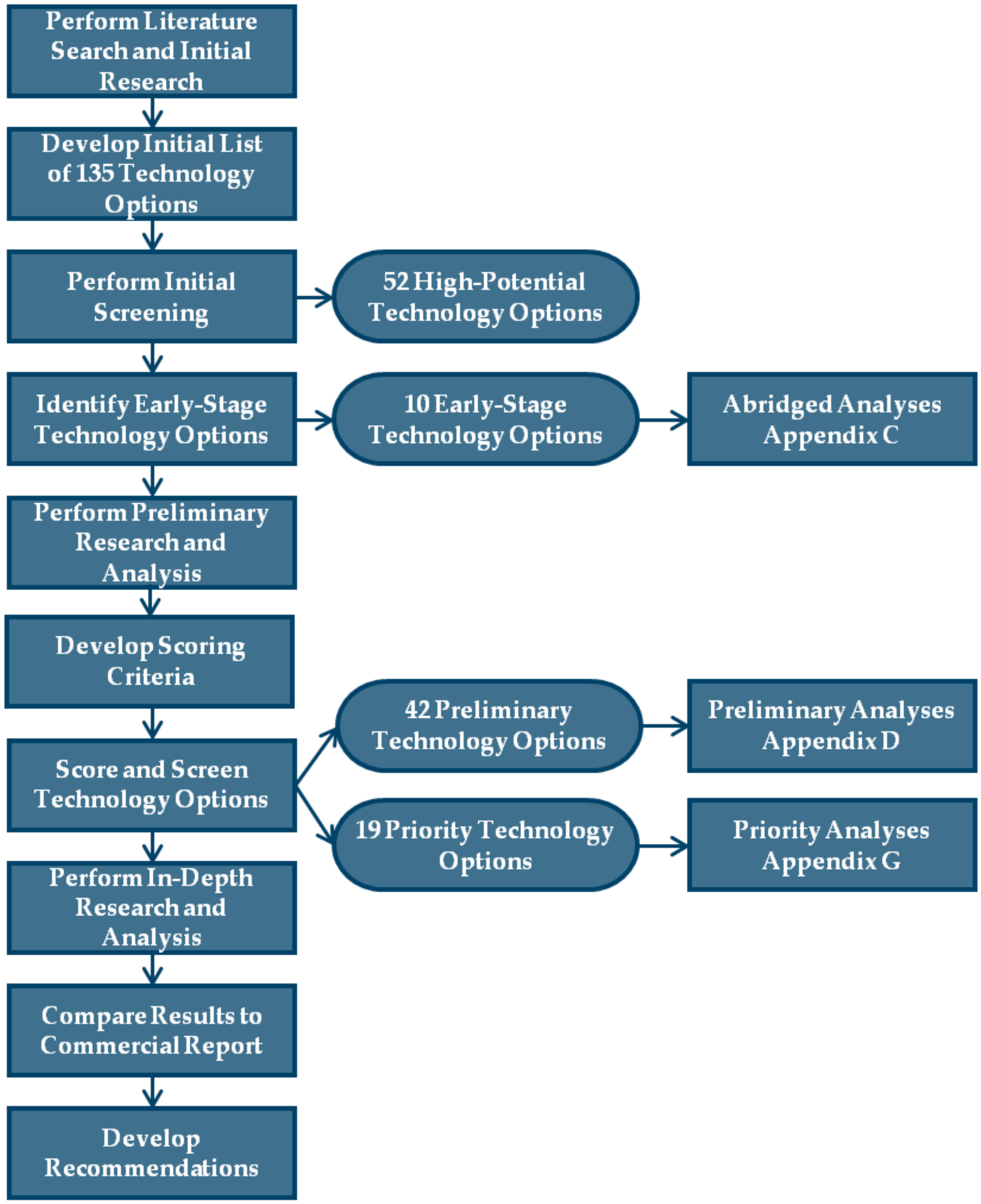


Figure 2-1. Technology Selection, Screening, and Assessment Process

2.1 Develop Initial List of Technology Options

We first generated the initial, comprehensive list of technology options that could potentially improve the efficiency of residential HVAC systems, resulting in 135 technology options (see Appendix A). We compiled this list without considering the economics, technical maturity, or the level of expected energy savings (if any). The only criteria for inclusion in this list were that the technology option must be directly applicable to HVAC systems in residential buildings, and have a potential to reduce HVAC energy consumption in some way. We define an HVAC system as an active system performing heating, cooling, or ventilation, separate from the building envelope. We excluded certain options such as real-time pricing, which are upstream of the HVAC system.

We identified the technology options included in the initial list through a variety of sources, including:

- HVAC Industry Organizations, Publications, and Websites (e.g., ASHRAE, AHRI, ACHR, and JARN)
- U.S. and International Government Organizations and National Laboratories (e.g., LBNL, CEC, NYSERDA, and ARPA-E)
- University Research (e.g., University of Maryland, Purdue University, University of Illinois, and Texas A&M University)
- HVAC Manufacturers (e.g., Trane, Daiken, Honeywell, and Johnson Controls)
- Internal Sources and HVAC Experts.

Appendix B documents the sources used to develop the initial list of technology options.

After compiling the initial, comprehensive list of technology options, we conducted a literature review for each option to develop technical descriptions and energy savings projections, and identify equipment/systems to which technology option is potentially applicable.

2.2 Develop the Initial Screening Criteria / Identify Technology Options for Preliminary Analyses and Separate Early-Stage Technology Options

2.2.1 Initial Screening Process

After assembling the initial list of 135 technology options, we developed a set of criteria to screen these options to identify those warranting further evaluation. We screened out 83 technology options because they did not meet one or more of the criteria listed below:

1. **Technology options that are outside the scope of this study:** Technology options considered outside the scope of this study included building design, envelope, and lighting strategies that reduced HVAC energy consumption indirectly. For example, improving building insulation reduces HVAC energy waste, but is not itself part of HVAC equipment or systems.
2. **Technology options at the end of their development cycle:** Technology options that are either widely practiced in the HVAC industry or otherwise fully developed into a commercially available product.
3. **Technology options with limited or no energy savings impact:** Technology options having documented unit energy savings of less than 15% for the overall HVAC system, or less than 15% performance improvement for a particular component, were not considered for further analysis. These technology options may reduce material, utilize alternative refrigerants, lower operating costs, etc.
4. **Technology options with limited applicability to residential HVAC:** Technology options that do not have potential for widespread use in residential HVAC applications, but are developed primarily for other purposes such as refrigeration, automotive A/C, and

industrial processes. If these technology options were used for residential buildings, they would apply only for niche applications.

2.2.2 Identification of Early-Stage Technology Options

We found a paucity of publicly available information for 10 technology options that are still in the early stages of R&D. Because we were unable to find energy and cost savings estimates for these options, we could not quantitatively compare them to other options. Thus, we removed them from the scoring and screening process and made separate recommendations for DOE, described in Section 5.4.1. Table 2-1 shows the 10 early-stage technology options and the annual energy consumption of baseline technology potentially affected. Section 4 summarizes these 10 technology options, with the abridged analyses located in Appendix C.

Table 2-1. The 10 Early-Stage Technology Options and the Annual Energy Consumption of Baseline Technology

Early-Stage Technology Option	Annual Energy Consumption of Baseline Technology (Quads/yr)
Active Modular Phytoremediation Wall	**4.06**
Advanced Membrane Heat Pump	**1.53**
Air-Bearing Heat Exchanger	**3.06**
Bernoulli Heat Pump	**1.74**
Binary Fluid Ejector	**0.21**
Co-Fluid Vapor Compression	**1.74**
Metal-Foam Heat Exchanger	**3.79**
Self-Cleaning Heat Exchanger	**2.53**
Thermoelastic Cooling System	**1.74**
Turbo-Compressor-Condenser-Expander	**1.74**

2.2.3 Grouping of Technology Options for Preliminary Analysis

After separating early-stage technology options from the list, we grouped the remaining 42 technology options, shown in Table 2-2, selected for preliminary analysis to better understand their technical energy savings potential for residential HVAC systems. We grouped these technology options as follows:

- **Components:** Technology options implemented within the HVAC equipment to improve the efficiency (individual parts or features)
- **Equipment:** Technology options that improve the way heating or cooling is generated (e.g., cooling cycles, heat pumps).

- **Distribution Systems:** Approaches/strategies that efficiently distribute cooling/heating throughout the living space and maintain optimum space comfort and IAQ through improved techniques
- **Installation, Operations and Maintenance (O&M):** Approaches/strategies to identify and remediate causes of poor system efficiency and maintain performance throughout the life of the HVAC system
- **Controls, Behavior Modification:** Control strategies and approaches that impact HVAC energy consumption by influencing resident behavior and practices
- **Community-Based Systems:** Technology options designed to provide space conditioning for multiple buildings or homes in a local residential community for the purpose of improving energy efficiency.
-

Table 2-2. 42 Technology Options Selected for Preliminary Analysis

Components (7)	Equipment (17)
Advanced Defrost Methods for Heat Pumps	Advanced Evaporative Coolers
Brushless Direct-Current Motors	Ductless Multi-Split System
Microchannel Heat Exchanger	Evaporatively Cooled Condensers
Smaller Centrifugal Compressors	Gas Engine-Driven Heat Pump
Smart Refrigerant Distributors	Gas-Fired Absorption Heat Pump
Thermoelectrically Enhanced Subcoolers	Geothermal Heat Pump
Variable-Stroke Compressor	Heat Pump for Cold Climates
Distribution Systems (10)	Hot-Dry Air Conditioner
Air-Ground Heat Exchanger	Hybrid Geothermal Heat Pump
Airflow-Optimizing System	Integrated Heat Pump
Chilled-Beam Radiant Cooling	Liquid-Desiccant Air Conditioner
Ductwork in the Conditioned Space	Magnetic Cooling System
Evaporative Roof Cooling	Nighttime Ventilation Cooling
Improved Duct Systems	Smart Ceiling-Fan Controls
Mixed-Mode Conditioning	Smart Ventilation Systems
Night Sky Radiant Cooling	Thermoelectric Cooling System
Seasonal Thermal Energy Storage	Thermotunneling Cooling System
Swimming-Pool Heat Sink	**Controls, Behavior Modification (2)**
Installation, Operations and Maintenance (5)	Home Energy Management System
Aerosol Duct Sealing	Learning Thermostats
Central A/C and Heat Pump Fault Detection and Diagnostics	**Community-Based Systems (1)**
Quality Installation	District Heating and Cooling
Regular Maintenance	
Retrocommissioning	

2.3 Perform Preliminary Analyses for the Selected Technology Options

For each of the 42 options, we estimated the annual technical energy savings potential in the U.S. residential-building sector, and compiled projections of the installed costs. Further, we identified barriers to market adoption and potential next steps toward greater market adoption for each of the technology options. Appendix D contains the preliminary analysis reports for the 23 technology options not selected for the in-depth analysis.

2.3.1 Overview of the Preliminary Analysis

During the preliminary analysis, we researched a number of characteristics for each selected technology option, as seen in Table 2-3.

Table 2-3. Preliminary Analysis Technology Characteristics

Technology Characteristic	Description
Projected Technical Energy Savings Potential	Technical energy savings potential is the theoretical national primary energy savings that could be achieved if all technically suitable installations are replaced with a particular energy-saving technology. See Section 2.3.2.
Projected Installed Costs	We identified representative installed costs for each technology option as cited in the literature and by expert sources. For options currently in the research and development (R&D) stage, there may be significant uncertainties in current cost projections.
Replacement Potential	We assessed replacement potential based on how difficult the technology option would be to implement in existing buildings, and on how invasive it might be once implemented.
Peak-Demand Reduction and Other Non-Energy Benefits	Non-energy benefits add value beyond gas or electric energy savings, and may benefit the environment, building owners, or occupants. They can be either quantitative or qualitative, and can vary greatly by system type and building application.
Technical Maturity	Technology options may fall in one of the following categories for technical maturity: • Commercially Available Technology: Commercially available in the U.S. • Emerging Technology: Limited/no availability in the U.S. market today, but may be commercially available outside the U.S., ready for commercialization in the U.S. without further R&D, or both • R&D Technology: Not commercially available; requires resolution of significant technical issues.

2.3.2 Estimating Technical Energy Savings Potential

As discussed in Section 1.2, we compiled HVAC energy-usage data from the 2010 BEDB and the 2009 RECS[5]. The BEDB is a compendium of data sources that provide high-level energy-usage characteristics, whereas RECS data are based on a statistical analysis of survey responses from occupants and owners of residential buildings and can provide more precise information on equipment usage within climate zones. Because these two sources derive their information differently, discrepancies can occur depending how the data is tabulated.

[5] 2009 RECS PUMF.

First, we estimated the total residential HVAC energy usage based on the BEDB by energy source. Because the full 2009 RECS data were unavailable, we estimated the energy consumption for each equipment type by climate zone by multiplying the following:

- The number of homes using each applicable equipment type according to climate zone from RECS 2009
- The average heating and cooling energy consumption per household by climate zone from RECS 2005.

Accounting for discrepancies between the two sources, we scaled the equipment and climate zone estimates derived from the RECS data to match the total residential HVAC usage provided by the BEDB. We then divided this estimate into several segments based on 2009 RECS, according to applicable equipment type, climate zone, and building type to determine the total energy usage that the technology option would impact. We then judged the viable applications (market segments) for each technology.

To determine technical energy savings potential, we multiplied the estimated percent unit energy savings by the total energy usage attributed to the technology.[6] Technical energy savings potential is the theoretical national primary energy savings that could be achieved if all technically suitable installations are replaced with a particular energy-saving technology. Unless specifically noted, we compared each technology to a baseline technology that meets current codes and standards (or current typical practice for new equipment installations) for U.S. residential buildings. Appendix E presents the technical energy savings potential for the technology options selected for preliminary analysis (listed in Table 2-2).

For the purposes of this study, we estimated baseline technology performance from information obtained through our literature search. Technical energy savings potential provides an upper bound for the maximum energy savings that could be achieved nationally through full adoption of the technology, without considering economics and other market-adoption constraints. Technology options may achieve a similar energy-saving goal through different approaches. For these technology options, the technical energy savings would not normally be additive.

We estimated technical energy savings potential for each technology option based on the following assumptions:

1. Using the technology option in all technically feasible applications, unless noted otherwise. In some cases, we excluded certain DOE climate zones that we determined to be poor fits.

2. Unless noted otherwise, we used the following guidelines to quantify replacement potential (qualitatively described in Section 2.3.1 above) based on technical fit:

[6] Where appropriate, we converted efficiency improvements into energy savings by relating the system efficiency to original energy use. For example, if efficiency improves 10%, energy use is divided by 110% (= 1.1), resulting in energy savings of 9.1% ($= 1 - \frac{1}{1.1}$).

a. ***High Replacement Potential***: Easily swapped for existing components, added onto existing systems without excessive changes, or installed as part of high-efficiency replacement equipment. Technology applies to 100% of the existing applicable installations.
b. ***Medium Replacement Potential***: Could be implemented without major structural changes to the building, especially during a major renovation, or if certain infrastructure were already in place (e.g., pipes and ducts). Technology applies to 50% of the existing applicable installations.
c. ***Low Replacement Potential***: Requires major structural changes to the building that would require a major building redesign to accommodate the new HVAC system. Technology applies to 5% of the existing applicable installations.

3. Each technology option is implemented properly so that it will achieve the expected energy performance.

4. Technology options requiring further R&D will achieve the energy performance currently predicted.

5. In cases where a technology option eliminates inefficiencies in existing equipment, equipment is restored to the performance levels expected with proper installation/operation/maintenance.

6. Technology options that improve motor efficiency are applied to all HVAC motors.

7. Every 10% improvement in heat-exchanger performance produces a 1% improvement in system-level performance.

2.4 Develop Scoring Criteria to Evaluate the Selected Technology Options

After analyzing the 42 technology options, we conducted another round of technology screening based on five criteria, as seen in Table 2-4.

Table 2-4. Scoring Criteria for Second Round of Technology Screening

Technology Characteristic	Description
Technical Energy Savings Potential	Technical energy savings potential is the theoretical national primary energy savings that could be achieved if all technically suitable installations are replaced with a particular energy-saving technology. See Section 2.3.1.
Fit with DOE BTP Mission	We considered fit with the DOE BTP mission to be high when: • The technology is much more likely to achieve success, or likely to achieve success much faster, with DOE support. • The technology's technical risk is moderate to high, rather than low or very high. • The technology, once developed, is likely to be embraced by major industry stakeholders.
Cost/Complexity	Based on the incremental first cost of the technology option and the incremental complexity associated with installation, operation, and maintenance of the technology option
Non-Energy Benefits	Based on the potential for the technology option to provide benefits beyond energy savings and direct emissions reduction, including but not limited to: improved comfort, improved indoor air quality, simplified maintenance, and reduced noise/vibration
Peak-Demand-Reduction Potential	Based on the technology option's potential to reduce peak electricity demand. While electric energy savings generally provide reductions in peak demand, some technology options save energy preferentially during off-peak hours. Furthermore, technology options that save gas, but not electricity, have no impact on peak electrical demand.

We assigned each criterion a weighting factor to reflect its overall importance. We scored each technology option (using a five-point scale) against each criterion, and calculated an overall score by multiplying the initial score by the weighting factor. Table 2-5 shows the scoring matrix and weighting factors for each criterion. Appendix F contains scoring results for each technology option.

Table 2-5. Technology Scoring Matrix

Screening Criteria	Wt. Factor	Score				
		1	2	3	4	5
Technical Energy Potential	**35%**	< 0.05 Quads/yr	0.05 – 0.1 Quads/yr	0.1 – 0.25 Quads/yr	0.25 – 0.5 Quads/yr	> 0.5 Quads/yr
Fit with DOE BTP Mission	**30%**	Very weak fit	Moderately weak fit	Neither strong nor weak fit	Moderately strong fit	Very strong fit
Cost/Complexity	**15%**	Much higher cost/ complexity	Moderately higher cost/ complexity	Slightly higher cost/complexity	Potential for similar cost/ complexity	Potential for lower cost/complexity
Other Non-Energy Benefits	**15%**	Provides few or no benefits	Likely to provide some modest benefits	Potential for significant benefits, but not well understood	Provides 1 or 2 quantified, well-documented benefits	Provides extensive, quantifiable, well-documented benefits
Peak-Demand-Reduction Potential	**5%**	No potential for reduction	0–5% reduction	5–10% reduction	10–15% reduction	> 15% reduction

2.5 Select Priority Technology Options and Perform In-Depth Analyses

After establishing the scoring criteria for the second round of technology screening and removing early-stage technology options from consideration, we scored each of the remaining 42 technology options based on our research and the input of internal HVAC experts. Through this process, we identified 19 priority technology options that clearly scored above the rest and best met the objectives of this study. We detail our 19 priority technology options in Section 3.

3 Summary of the 19 Priority Technology Options

This section summarizes the 19 priority technology options and details their technical energy savings potential. Appendix G provides detailed write-ups for each of the 19 priority technology options. Many of these technology options improve efficiency or enhance performance of common HVAC systems and problems, as categorized below:

- **Advanced Component Technology Options** offset the energy consumption of conventional HVAC systems by optimizing the performance of critical components.
- **Alternative Heating and Cooling Technology Options** provide heating or cooling more efficiently using novel techniques, or non-vapor-compression refrigeration cycles.
- **Advanced Heat Pump Technology Options** raise the efficiency and capabilities of current vapor-compression heat pumps through various enhancements and strategies.
- **High-Performance System Design and Restoration Technology Options** improve the lifetime performance and energy efficiency of residential HVAC systems by reducing common losses.
- **Intelligent Controls and Diagnostic Technology Options** maximize the performance of HVAC systems by restoring efficient operation after fault detection, and optimizing system controls through occupancy-based strategies.

These categories represent the numerous areas in need of efficiency improvement and the diversity of strategies available to reduce HVAC energy consumption in residential buildings. Table 3-1 provides each category with its corresponding technology options selected for in-depth analysis.

Table 3-1. Priority Technology Options by Category

Technology Category	Technology Option	Technical Energy Savings Potential (Quads/yr)
Advanced Component Technology Options	**Brushless Direct-Current Motors**	0.38
	Smart Refrigerant Distributors	0.28
Alternative Heating and Cooling Technology Options	**Gas-Fired Absorption Heat Pump**	0.66
	Thermoelectric Cooling System	0.58
	Thermoelectrically Enhanced Subcoolers	0.28
	Thermotunneling Cooling System	0.23
Advanced Heat Pump Technology Options	**Ductless Multi-Split System**	0.22
	Gas Engine-Driven Heat Pump	0.15
	Geothermal Heat Pump	0.48
	Heat Pump for Cold Climates	0.27
	Hybrid Geothermal Heat Pump	0.38
	Integrated Heat Pump	0.55
High-Performance System Design and Restoration Technology Options	**Aerosol Duct Sealing**	0.30
	Regular Maintenance	0.83
	Retrocommissioning	1.62
Intelligent Controls and Diagnostic Technology Options	**Central A/C and Heat Pump Fault Detection and Diagnostics**	0.40
	Home Energy Management System	0.37
	Learning Thermostat	0.74
	Smart Ceiling-Fan Controls	0.02

3.1 Advanced Component Technology Options

Advanced Component Technology Options optimize the performance of critical components, offsetting energy consumption for conventional HVAC systems. Table 3-2 provides a brief description and technical energy savings potential for the technology options selected for in-depth analysis within the Advanced Component Technology Options category. Appendix G.1 provides detailed write-ups for each of the priority technology options in this category.

Table 3-2. Priority Technology Options within the Advanced Component Technology Options Category

Technology Option	Brief Description	Technical Energy Savings Potential (Quads/yr)
Brushless Direct-Current Motors	Brushless direct-current (BLDC) motors use electronic controls to control speed and reduce energy losses, improving efficiency. **Cost/Complexity:** Medium-High **Technical Maturity:** Emerging	**0.38**
Smart Refrigerant Distributors	Refrigerant maldistribution in evaporators lowers capacity and efficiency in vapor-compression systems. Smart refrigerant distributors sense and direct the proper amounts of refrigerant to each evaporator circuit, thereby maintaining optimum performance. **Cost/Complexity:** Medium **Technical Maturity:** Emerging	**0.28**

3.2 Alternative Heating and Cooling Technology Options

Alternative Heating and Cooling Technology Options provide thermal conditioning using alternatives to the vapor-compression refrigeration cycle. To be included in this category, a technology option must at least have the potential to be more energy efficient than conventional vapor-compression heating and/or cooling. Table 3-3 provides a brief description and technical energy savings potential for the technology options selected for in-depth analysis within the Alternative Heating and Cooling Technology Options category. Appendix G.2 provides detailed write-ups for each of the priority technology options in this category.

Table 3-3. Priority Technology Options within the Alternative Heating and Cooling Technology Options Category

Technology Option	Brief Description	Technical Energy Savings Potential (Quads/yr)
Gas-Fired Absorption Heat Pump	Modern gas-fired furnaces and boilers can achieve efficiencies close to the theoretical limit for combustion appliances (100%). A gas-fired absorption heat pump (GAHP) using a water-ammonia absorption cycle can exceed the thermal output of natural gas combustion to provide space heating at COPs ranging from 1.4-1.7. **Cost/Complexity:** Medium **Technical Maturity:** Emerging	**0.66**
Thermoelectric Cooling System	Under an applied voltage, thermoelectric materials generate a temperature difference that can provide residential space conditioning. Although currently limited to niche applications, future developments could raise the efficiency and capacity of thermoelectrics to be a non-refrigerant-based replacement for conventional cooling systems. **Cost/Complexity:** High **Technical Maturity:** R&D	**0.58**
Thermoelectrically Enhanced Subcoolers	Imbedded thermoelectric devices that convert electricity into a thermal gradient can provide condensed-refrigerant subcooling to increase evaporator capacity and COP more efficiently than other subcooling methods. **Cost/Complexity:** Medium **Technical Maturity:** R&D	**0.28**
Thermotunneling Cooling System	Thermotunneling cooling system is an advanced form of thermoelectric cooling that transmits electrons across a vacuum to obtain cooling and heating. Although modeling suggests large potential energy savings, this solid-state technology requires additional long-term research to solve a number of technical concerns. **Cost/Complexity:** High **Technical Maturity:** R&D	**0.23**

3.3 Advanced Heat-Pump Technology Options

Technology options in this category improve on current vapor-compression heat-pump designs through the use of novel heat exchangers or other high-efficiency components and innovative control strategies. Table 3-4 provides a brief description and technical energy savings potential for the technology options selected for in-depth analysis within the Advanced Heat Pump Technology Options category. Appendix G.3 provides detailed write-ups for each of the priority technology options in this category.

Table 3-4. Priority Technology Options within the Advanced Heat-Pump Technology Options Category

Technology Option	Brief Description	Technical Energy Savings Potential (Quads/yr)
Ductless Multi-Split System	Ductless multi-split (DMS) or variable refrigerant flow systems (VRF) connect multiple indoor units with a single outdoor unit to provide efficient space heating and cooling. DMS minimize distribution losses common to ducted HVAC systems, and offer improved efficiency over electric-resistance heating. **Cost/Complexity:** Medium **Technical Maturity:** Commercially Available	**0.22**
Gas Engine-Driven Heat Pump	Instead of utilizing an electrically driven compressor, a gas engine-driven heat pump (GEHP) drives the compressor using the mechanical output of an engine, saving energy in two ways: 1) eliminating some of the losses associated with generating and delivering electric energy, and 2) capturing waste heat from the engine and exhaust. **Cost/Complexity:** Medium **Technical Maturity:** Emerging	**0.15**
Geothermal Heat Pump	Geothermal heat pumps utilize alternative thermal sources/sinks to operate a vapor-compression heat pump more efficiently. Although these systems have been installed in the U.S. for decades, GHPs using high-efficiency components, alternative loop designs, advanced drilling techniques, and better field measurement strategies could lower the upfront cost of these systems and increase their market adoption. **Cost/Complexity:** High **Technical Maturity:** Emerging	**0.48**
Heat Pump for Cold Climates	Heat pumps for cold climates are air-source heat pumps with improved efficiency and capacity at lower temperatures (HSPF >9.5). **Cost/Complexity:** Medium **Technical Maturity:** Commercially Available	**0.27**
Hybrid Geothermal Heat Pump	Hybrid geothermal heat pumps decrease the required size of the ground-coupled heat exchanger by using auxiliary, above-ground equipment during peak loads, providing comparable energy savings and improved economics for GHP applications. **Cost/Complexity:** High **Technical Maturity:** Emerging	**0.38**
Integrated Heat Pump	The integrated heat pump (IHP) supplies space heating, space cooling, and domestic hot water, on demand, using a vapor-compression heat pump. **Cost/Complexity:** High **Technical Maturity:** Emerging	**0.55**

3.4 High-Performance System Design and Restoration Technology Options

Technology options in this category reduce losses associated with improper contractor system design and installation, degradation of equipment over time, and other factors that diminish the performance of installed residential HVAC systems. Table 3-5 provides a brief description and technical energy savings potential for the technology options selected for in-depth analysis within the High-Performance System Design and Restoration Technology Options category.

Appendix G.4 provides detailed write-ups for each of the priority technology options in this category.

Table 3-5. Priority Technology Options within the High-Performance System Design and Restoration Technology Options Category

Technology Option	Brief Description	Technical Energy Savings Potential (Quads/yr)
Aerosol Duct Sealing	When introduced in duct systems, aerosol duct sealants selectively deposit around holes, plugging leaky ducts without having to locate and access the holes. By decreasing duct leakage, a greater percentage of the thermal energy reaches its intended space, reducing thermal and fan energy consumption. **Cost/Complexity:** Medium **Technical Maturity:** Commercially Available	**0.30**
Regular Maintenance	Regular maintenance is servicing of HVAC equipment as recommended by the manufacturer to, in part, minimize efficiency degradation over time. **Cost/Complexity:** Medium **Technical Maturity:** Emerging	**0.83**
Retrocommissioning	Residential retrocommissioning (RCx) is the process of assuring an existing home achieves energy efficiency that it was designed to achieve. **Cost/Complexity:** Medium **Technical Maturity:** Commercially Available	**1.62**

3.5 Intelligent Controls and Diagnostic Technology Options

Technology Options in this category maximize the performance of HVAC systems by controlling operations based on home-occupancy patterns, or by identifying inefficient performance so that maintenance personnel can make the necessary repairs, replacements, and adjustments. Table 3-6 provides a brief description and technical energy savings potential for the technology options selected for in-depth analysis within the Intelligent Controls and Diagnostic Technology Options category. Appendix G.5 provides detailed write-ups for each of the priority technology options in this category.

Table 3-6. Priority Technology Options within the Intelligent Controls and Diagnostic Technology Options Category

Technology Option	Brief Description	Technical Energy Savings Potential (Quads/yr)
Central A/C and Heat Pump Fault Detection and Diagnostics	Fault detection and diagnostic (FDD) systems alert homeowners of common problems associated with residential split-system air conditioners and heat pumps. By identifying performance deviation and determining its cause, directed maintenance can restore the equipment to peak efficiency. **Cost/Complexity:** Medium **Technical Maturity:** Emerging	**0.40**
Home Energy Management System	A home energy management system employs various energy management and information tools to promote energy savings via home occupant education and feedback. **Cost/Complexity:** High **Technical Maturity:** Emerging	**0.37**
Learning Thermostat	The learning thermostat improves upon a conventional programmable thermostat by automating temperature-schedule creation based on initial user inputs and occupancy habits. **Cost/Complexity:** Medium **Technical Maturity:** Emerging	**0.74**
Smart Ceiling-Fan Controls	Operating a ceiling fan allows the thermostat to be set 2-4°F higher during the cooling season while maintaining similar comfort levels for occupants. In combination with raised temperatures, smart ceiling-fan controls using occupancy sensors operate only when a room is occupied, reducing ceiling-fan energy consumption. **Cost/Complexity:** Medium **Technical Maturity:** Emerging	**0.02**

4 Summary of the 10 Early-Stage Technology Options

During our research, we identified a small number of technology options for which there was a paucity of publicly available information, because they are still in the early stages of R&D. Because we were unable to find credible energy and cost savings estimates for these technology options, we could not evaluate them against the other technology options. Thus, we removed them from consideration for the list of priority technology options, but made separate recommendations for DOE, described in Section 5.4.1. Table 4-1 provides a brief description for each of the 10 early-stage technology options and the annual energy consumption of baseline technology. Appendix C provides an abridged analysis for each of the early-stage technology options.

Table 4-1. Summary of 10 Early-Stage Technology Options

Technology Option	Brief Description	Annual Energy Consumption of Baseline Technology (Quads/yr)
Active Modular Phytoremediation Wall	The Active Modular Phytoremediation System uses hydroponic plant roots to remove toxins from the air.	**4.06**
Advanced Membrane Heat Pump	Driven by a compressor, advanced-membrane heat pumps provide cooling/dehumidification and/or heating/humidification by transferring moisture across a number of membranes.	**1.53**
Air-Bearing Heat Exchanger	The air-bearing heat exchanger uses a rotating, bladed heat sink separated by a small gap of air to reduce the boundary layer in a condenser or evaporator heat exchanger.	**3.06**
Bernoulli Heat Pump	Bernoulli heat pumps centrifugally accelerate a working fluid through a spinning nozzle to produce cooling.	**1.74**
Binary Fluid Ejector	The binary-fluid ejector is specifically designed for two fluids; one fluid optimizes refrigeration efficiency, while the other optimizes the ejector efficiency.	**0.21**
Co-Fluid Vapor Compression	A heat pump utilizing a two-phase co-fluid can provide space conditioning by controlling heat transfer as an ionic liquid absorbs/desorbs CO_2.	**1.74**
Metal-Foam Heat Exchanger	Metal-foam heat exchangers use porous metal to allow a working fluid to pass through, increasing surface area and turbulent flow to improve heat transfer.	**3.79**
Self-Cleaning Heat Exchanger	The self-cleaning furnace heat exchanger uses turbulent flow or brushes to remove scaling from heat-exchanger surfaces.	**2.53**
Thermoelastic Cooling System	Using the unique properties of smart-memory alloys (SMA), thermoelastic cooling systems twist and release an SMA core that absorbs heat from its surroundings.	**1.74**
Turbo-Compressor-Condenser-Expander	This technology combines the compressor, condenser, and expansion device of a typical vapor-compression system into an integrated package for greater heat-transfer efficiency.	**1.74**

5 Conclusions

We identified a wide range of technology options having the potential to reduce residential HVAC energy consumption. This section:

- Summarizes the screening process through which we identified the priority technology options on which to perform in-depth analyses
- Discusses general observations regarding the current state of development for the 19 priority technology options
- Compares the list of the 19 priority technology options to the technology options included in a recently completed commercial HVAC study (Goetzler et al. 2011)
- Identifies 10 technology options that we could not evaluate and screen based on available information (early-stage technology options)
- Recommends RD&D initiatives that would help advance the early-stage and priority technology options for both residential and commercial applications.

5.1 Summary of the Technology Screening Process

We identified a wide range of technology options having the potential to reduce residential HVAC energy consumption in U.S. buildings. These included energy-saving HVAC technology options at various stages of development, from those in proof-of-concept research to those that are currently available on the market. Over the course of this study, our technology selection and screening process included the following steps:

- Developed a comprehensive list of 135 technology options through a literature survey and performed initial research
- Selected 52 technology options through an initial screening process, and identified 10 early-stage technology options to be evaluated separately,[7] resulting in a net of 42 technology options for preliminary analysis
- Analyzed these 42 technology options, established scoring criteria for the second round of technology screening, and scored each of the 42 technology options based on our research and the input of internal HVAC experts[8]
- Performed an in-depth analysis of each of the 19 priority technology options that best fit the objectives of this study and clearly scored above the others[9]

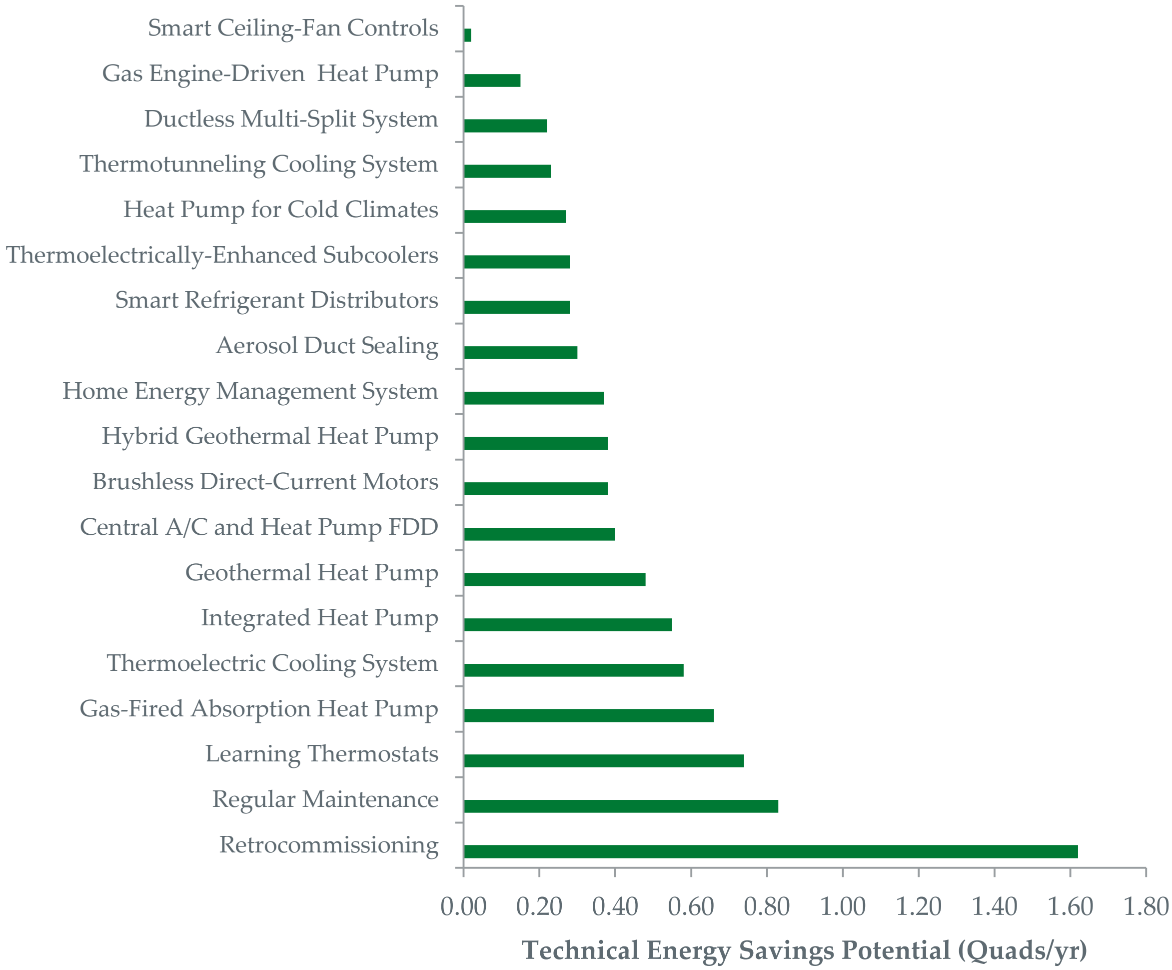
We analyzed in detail the 19 priority technology options and recommended next steps for their continued development. Each of the 19 priority technology options features significant technical energy savings potential[10] (see Figure 5-1). In some cases, multiple technology options target the same savings opportunity through different approaches (e.g., Retrocommissioning and Regular Maintenance). Therefore, the technical energy savings potentials are not additive.

[7] Summarized in Section 4 and in Appendix C.

[8] Appendix D includes preliminary analyses of the 23 technology options analyzed after the initial screening, but not selected for in-depth analyses nor designated as early-stage technology options.

[9] Summarized in Section 3 and in Appendix G.

[10] Technical energy savings potential is the theoretical national primary energy savings that could be achieved if all technically suitable installations are replaced with a particular energy-saving technology.



Note: Potential savings are not additive for most technology options and applications.

Figure 5-1. Technical Energy Savings Potential for the 19 Priority Technology Options

Because technical energy savings potential depends both on the applicability of the technology option across HVAC equipment/systems and the projected unit energy savings, technology options that address both heating and cooling (e.g., Integrated Heat Pump) or benefit multiple HVAC system types (e.g., Retrocommissioning) have larger technical energy savings potentials. Technology options that are readily retrofit into existing buildings either as a supplementary system (e.g., Learning Thermostat), or that could be integrated in replacement equipment (e.g., Central A/C and Heat Pump FDD), have higher technical energy savings potentials as well.

5.2 Observations on the 19 Priority Technology Options

5.2.1 Technology Categories

We analyzed a wide spectrum of technology options available for achieving HVAC energy savings in U.S. residential buildings. Table 5-1 describes the five technology categories by which we grouped the technology options. The categories represent a top-level breakdown of the complex HVAC systems used in residential applications.

Table 5-1. Descriptions of the Categories for Grouping the 19 Priority Technology Options

Category	Energy Savings Opportunity
Advanced Component Technology Options	Optimizing the performance of critical components offsets the energy consumption of conventional HVAC systems.
Alternative Heating and Cooling Technology Options	Novel technologies and strategies that can provide heating or cooling more efficiently that use alternatives to the vapor-compression refrigeration cycle.
Advanced Heat-Pump Technology Options	Innovative heat pump designs using alternative heat exchangers, high-efficiency components, innovative control strategies, and other features improve efficiency over current vapor-compression equipment.
High-Performance System Design and Restoration Technology Options	Comprehensive strategies intended to reduce common HVAC losses, and optimize the performance and efficiency of residential HVAC systems for both new and existing homes.
Intelligent Controls and Diagnostic Technology Options	Controlling system operations based on home occupancy patterns, or identifying inefficient equipment performance maximizes the performance and efficiency of residential HVAC systems.

5.2.2 Peak-Demand Reduction and other Non-Energy Benefits

In addition to reducing energy consumption, many of the priority technology options selected for in-depth analysis reduce peak demand or feature other non-energy benefits (Table 5-2). These additional benefits provide both qualitative and quantitative value to building owners and occupants. In some instances, the additional benefits offered by these technology options (e.g., improved occupant comfort, FDD capabilities/extends equipment life) may be as important to homeowners as HVAC energy savings. Electric utilities may be particularly interested in technology options offering significant potential for peak-demand reduction, and include them in demand-side management initiatives.

Table 5-2. Peak-Demand Reduction and other Non-Energy Benefits for the 19 Priority Technology Options

Technology Option	Other Applicable Benefits					
	Peak-Demand Reduction	Improved Occupant Comfort	Improved Indoor Air Quality	Noise Reduction	FDD Capabilities / Extends Equipment Life	Less Refrigerant Charge / Alternative Refrigerants
Aerosol Duct Sealing	✓	✓	✓	✓		
Brushless Direct-Current Motors	✓			✓	✓	
Central A/C and Heat Pump Fault Detection and Diagnostics	✓	✓			✓	
Ductless Multi-Split System		✓		✓		
Gas Engine-Driven Heat Pump	✓✓	✓				
Gas-Fired Absorption Heat Pump	✓✓					✓
Geothermal Heat Pump	✓✓	✓		✓	✓	
Heat Pump for Cold Climates	✓✓	✓				
Home Energy Management System	✓✓					
Hybrid Geothermal Heat Pump	✓					
Integrated Heat Pump	✓					
Learning Thermostats	✓					
Regular Maintenance	✓	✓	✓	✓	✓	
Retrocommissioning	✓	✓	✓		✓	
Smart Ceiling-Fan Controls	✓					
Smart Refrigerant Distributors		✓			✓	✓
Thermoelectric Cooling System	✓			✓	✓	✓
Thermoelectrically Enhanced Subcoolers	✓	✓				✓
Thermotunneling Cooling System	✓			✓		✓

Note: One check mark signifies technology options that lower peak demand in proportion to energy savings. Two check marks signify technology options that lower peak-demand beyond energy savings alone.

5.2.3 Technical Energy Savings Potential

As Figure 5-2 presents, the 19 priority technology options cover a broad range of development status. For R&D technology options, Figure 5-2 shows both conservative and more optimistic

("Max") projections of technical energy savings potential, the latter based on the most optimistic projections found in the literature.

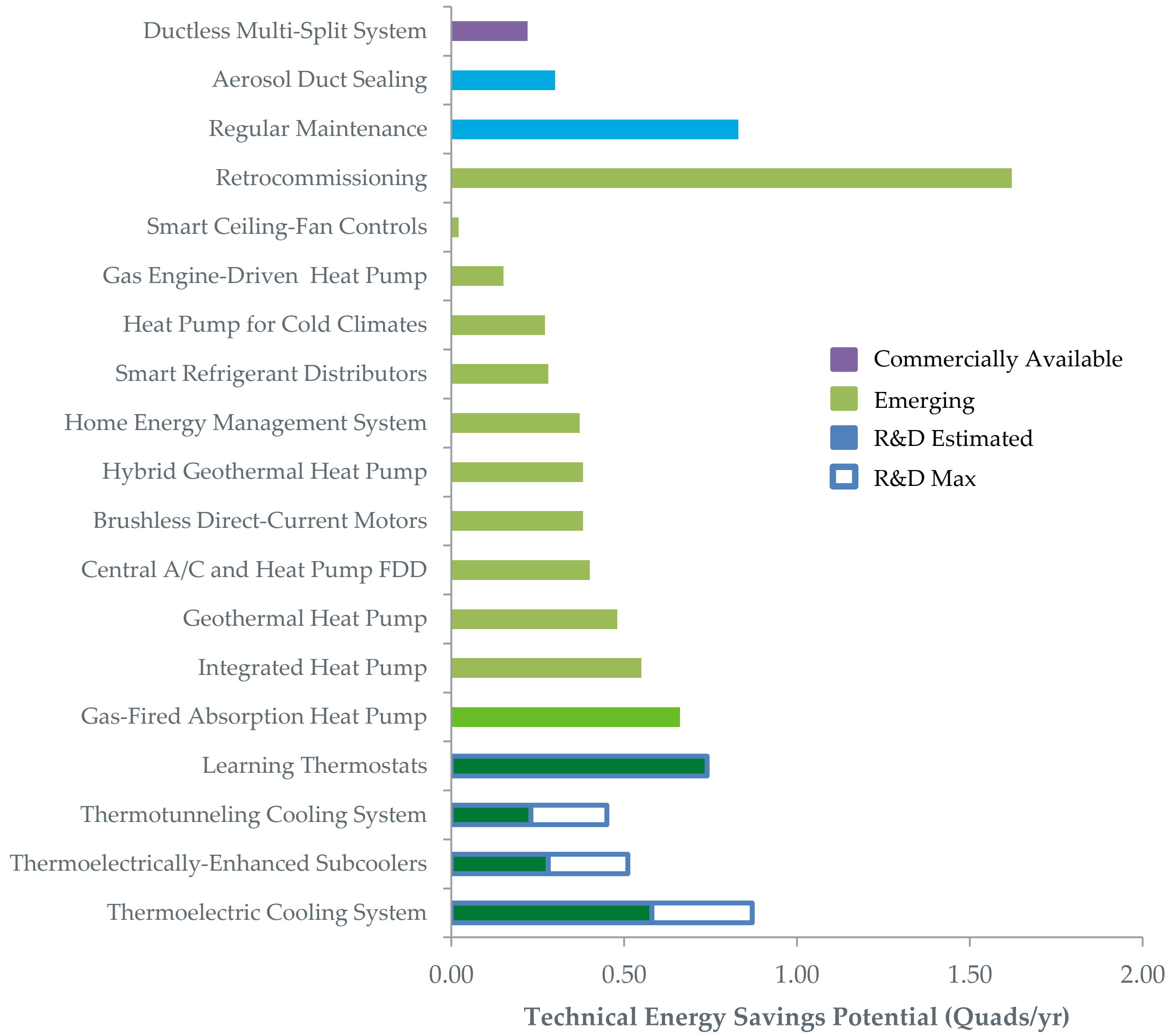


Figure 5-2. Technical Energy Savings Potential for the Priority Technology Options by Technical Maturity

Throughout this study, we used conservative projections for the technical energy savings potentials of technology options in the R&D phase for the following reasons:

- Significant advances in material science must occur for successful development of technology option for HVAC applications (e.g., Thermoelectric and Thermotunneling Cooling Systems).
- Initial laboratory performance looks promising on small-scale testing, but significant barriers exist for integration into full-scale HVAC systems (e.g., Metal-Foam Heat Exchangers).

- Lack of proven performance from testing in real-world conditions (e.g., Thermoelectrically Enhanced Subcoolers).

5.2.4 Cost and Complexity

For technology options not yet widely available, estimating the upfront cost and installation complexity becomes difficult. Key challenges include the following:

- Cost (and performance) claims by technology developers are often unsubstantiated, with few publicly available, independent, detailed examinations.
- After reaching technical maturity, the upfront costs for certain technology options can still vary widely, depending on site-specific conditions and operating characteristics.
- Uncertainties in cost associated with the current development status of the technology.

In most cases, we evaluated cost/complexity qualitatively, considering the incremental first cost and the added complexity associated with installation, operation, and maintenance for the technology option compared to conventional technology.

Given that the available information may be insufficient or unreliable for immature technology options, we focused our economic analysis on the technology options that are closer to commercialization. Developers of technology options in R&D stages often project costs based on large economies of scale and mature manufacturing techniques. Many of these technology options still require significant material-science improvements, and performance breakthroughs, to demonstrate technical viability in the marketplace. Nevertheless, some of these immature technology options may reduce equipment complexity because they have fewer moving parts, potentially lowering maintenance requirements and providing higher reliability.

Table 5-3 categorizes estimated cost/complexity for the technology options that are beyond early-stage R&D. For most of the technology options, potential energy savings impacts (and even first costs) vary widely depending on the specific building type, size, location, existing HVAC systems, etc. Even with this uncertainty, these technology options can likely provide significant energy savings with relatively favorable economics for a variety of residential applications, especially where HVAC loads are high. Appendix G discusses the cost/complexity for each priority technology option.

Table 5-3. Estimated Cost/Complexity for Technology Options Beyond Early-Stage R&D

Category	Technology Options
Slightly Higher Cost/Complexity	Central A/C and Heat Pump Fault Detection, and Diagnostics Learning Thermostat Regular Maintenance Retrocommissioning Smart Ceiling-Fan Controls Smart Refrigerant Distributors
Moderately Higher Cost/Complexity	Aerosol Duct Sealing Brushless Direct-Current Motors Ductless Multi-Split System Heat Pump for Cold Climates Integrated Heat Pump
Significantly Higher Cost/Complexity	Gas Engine-Driven Heat Pump Gas-Fired Absorption Heat Pump Geothermal Heat Pump Home Energy Management System Hybrid Geothermal Heat Pump

5.3 Comparison with 2011 Commercial HVAC Study

During our investigation, we did not identify any previous comprehensive studies of energy-efficient technologies for residential HVAC systems to which we could compare the results of this study. As discussed in Section 1.2 above, DOE BTP commissioned a study in 2011 to investigate energy-efficient technology options for commercial HVAC systems (Goetzler et al. 2011). Although the residential study documented herein followed a screening and scoring process similar to that used in the 2011 commercial report, the residential study produced a different set of priority technology options. This resulted primarily because of specific differences between residential and commercial HVAC systems in the U.S., which shaped the evaluation of technology options for each study. For example, space heating and heat-pump technologies represent a larger portion of annual HVAC energy usage for residential buildings, whereas ventilation has historically been a more important consideration for commercial buildings. Table 5-4 compares the technology options analyzed in-depth for this study to those analyzed in-depth in the 2011commercial study. Figure 5-3 presents the combined technical energy savings potential for the list of the priority technology options for both residential and commercial HVAC systems, sorted by technical maturity.

As seen in Table 5-4 and Figure 5-3, some of the priority technology options from both reports offer considerable energy savings for both residential and commercial HVAC systems, or have related attributes. In these instances, DOE BTP's role in advancing these technology options to wider adoption would be similar, if not the same. Because of the significant energy savings potential and similar development initiatives of the combined list, we recommend DOE BTP support the technology options prioritized in both this residential and the 2011 commercial study. See Section 5.4 for our specific recommendations.

Table 5-4. Comparison of Residential Technology Options Analyzed to Commercial Technology Options Analyzed by Goetzler et al. (2011)

Technology Options	Residential		Commercial		Notes
	Status	Savings (Quads/yr)	Status	Savings (Quads/yr)	
Central A/C and Heat Pump Fault Detection & Diagnostics	●	0.40	●	0.08	The methodology and equipment for fault detection and diagnostics are shared between both residential and commercial systems. The commercial study also considered fault detection and diagnostics, but focused on packaged rooftop units more commonly used on commercial buildings.
Retrocommissioning	●	1.62	●	0.87	Retrocommissioning offers large technical energy savings potential for both residential and commercial buildings.
Smart Refrigerant Distributors	●	0.28	●	0.09	Although manufacturers plan to initially offer this technology for residential split-systems, smart refrigerant distributors are equally applicable for packaged HVAC equipment for commercial buildings.
Thermoelectric Cooling System	●	0.58	●	0.36	These solid-state cooling technology options (still in the R&D phase) have significant technical energy savings potential for both residential and commercial applications.
Thermoelectrically Enhanced Subcoolers	●	0.28	●	0.20	
Thermotunneling Cooling System	●	0.23	●	0.10	
Aerosol Duct Sealing	●	0.30	(●)	0.91	For the residential study, we combined aerosol duct sealing and duct-leakage diagnostics because both strategies would likely be employed together for the simpler, residential duct systems. Although initially designed and primarily implemented for residential duct systems, these technology options are applicable to both residential and commercial buildings.
Home Energy Management System	●	0.37	(●)	0.53	The commercial study evaluated separately a) building energy information systems (performed in-depth analysis), and b) energy management systems (screened out). For residential applications, we assumed that these two technology options would be integrated into a single home energy management system that monitors, measures, and controls system operations.

● - *Included in the in-depth analysis* (●) - *Included in the in-depth analysis, but combined into one entry*

○ - *Considered in the study but was screened out* × - *Not considered in the study* *n/a – Not Available*

Table 5-4. Continued

Technology Options	Residential		Commercial		Notes
	Status	Savings (Quads/yr)	Status	Savings (Quads/yr)	
Brushless Direct-Current Motors	●	0.38	○	0.42	The residential study combined a number of motor technology options, which were evaluated separately in the commercial study, because the RD&D initiatives would likely be similar. Motor technology options in the commercial study include: copper-rotor motors, permanent magnet motors, and switched-reluctance motors. Brushless direct-current motors have higher importance for residential systems because variable-frequency inverter drives are less likely to be cost-effective for residential-sized motors compared to commercial applications, so an alternative is needed to achieve variable-speed operation in residential applications
Ductless Multi-Split System	●	0.22	○	0.19	Ductless multi-split systems (residential) and variable refrigerant flow (VRF) systems share the same technical concepts but typically differ on system size. The commercial study concluded that DOE does not play a major role in the development of VRF, because this technology option has started gaining acceptance for commercial buildings. DOE has a larger role for residential applications because VRF acceptance for multi-family buildings is relatively low, and ductless multi-split systems offer a significant energy savings opportunity for homes using resistance heating.
Gas Engine-Driven Heat Pump	●	0.15	○	n/a	Although applicable in the light-commercial market, the largest long-term potential for GEHPs and absorption heat pumps is in residential systems. While GEHPs and absorption heat pumps are currently available for light-commercial systems, there is a significant DOE role to adapt these technology options for typical residential applications.
Gas-Fired Absorption Heat Pump	●	0.66	○		
Geothermal Heat Pump (GHP)	●	0.48	○	n/a	While DOE has a role in improving the cost-effectiveness and promotion of GHPs for commercial buildings, the residential GHP market requires significant attention to address the high costs of system design and installation. For residential systems, these costs represent a larger portion of total installed cost and, hence, pose a greater cost barrier.
Heat Pump for Cold Climates	●	0.27	○	0.06	As a whole, split-system heat pumps are more commonly found in homes than businesses, so air-source heat pumps designed for cold climates offer greater energy savings for residential applications.
● - *Included in the in-depth analysis*			(●) - *Included in the in-depth analysis, but combined into one entry*		
○ - *Considered in the study but was screened out*			× - *Not considered in the study*		*n/a – Not Available*

Table 5-4. Continued

Technology Options	Residential		Commercial		Notes
	Status	Savings (Quads/yr)	Status	Savings (Quads/yr)	
Hybrid Geothermal Heat Pump	●	0.38	○	n/a	Although hybrid GHPs are currently not widely deployed, the majority of installations to date have been for commercial buildings, with limited research or design consideration to their applicability for residential systems. Residential hybrid designs could provide similar energy savings with less upfront cost compared to other GHP designs and should be investigated.
Learning Thermostats	●	0.74	○	n/a	The commercial study considered strategies for optimizing thermostat behavior, but, since that writing, learning thermostats have been introduced, primarily for residential systems, that show some promise.
Regular Maintenance	●	0.83	○	0.87	While many smaller commercial buildings lack good maintenance practices, larger commercial buildings tend to have better maintenance practices. In the residential sector, poor maintenance practices are the rule across the entire sector.
Integrated Heat Pump	●	0.55	×	n/a	As a whole, space-conditioning heat pumps are more commonly found in homes than businesses, so the residential sector offers a greater potential for integrated heat pumps compared to the commercial sector. However, there will be substantial spill-over benefit for light-commercial applications.
Smart Ceiling-Fan Controls	●	0.02	×	n/a	The commercial study considered large, low-velocity fans, but screened them out based on low energy savings related to their limited applicability. Ceiling fans are much more common in residential buildings.
Ductwork in the Conditioned Space	○	0.06	●	0.24	While placing ductwork within the conditioned space is important for residential buildings, it is primarily an opportunity for new construction, and therefore has a modest energy savings potential. For commercial buildings, there is more opportunity in existing buildings, which greatly expands its potential for energy savings.
Liquid-Desiccant Air Conditioner	○	0.03	●	0.21	Current liquid-desiccant air conditioners and the accompanying dedicated outdoor-air system are primarily applicable in larger multi-family and commercial buildings. The lower residential technical energy savings potential did not warrant in-depth analysis.

● - *Included in the in-depth analysis* (●) - *Included in the in-depth analysis, but combined into one entry*

○ - *Considered in the study but was screened out* × - *Not considered in the study* *n/a – Not Available*

Table 5-4. Continued

Technology Options	Residential		Commercial		Notes
	Status	Savings (Quads/yr)	Status	Savings (Quads/yr)	
Magnetic Cooling Cycle	○	0.35	●	0.18	Similar to other solid-state cooling technologies, the magnetic cooling cycle requires rare-earth metals to generate a flow of thermal energy. Magnetic cooling, however, requires significantly greater quantities of expensive rare-earth metals, posing an additional cost constraint on top of the already steep technical barriers. After careful evaluation of the economic considerations of rare-earth metals, we believe this issue would lead to inherently high costs even after future efficiency improvements, and would not be widely adopted in residential HVAC applications.
Demand-Controlled Ventilation	○	0.03	●	0.09	These two ventilation technology options featured in the commercial study were combined in the residential study, under the name of smart ventilation systems. While ventilation constitutes a significant portion of annual energy consumption for commercial buildings, efficient residential ventilation systems will become more important as building codes evolve to ensure good indoor air quality as allowable infiltration rates drop. This will primarily affect the new construction and major renovation markets, resulting in a low replacement potential for this study, currently. Potential energy savings in the future may be significantly higher as more homes contain ventilation systems.
Thermal Displacement Ventilation	○		●	0.18	
Continuous Commissioning	○	n/a	●	1.11	This technology option requires dedicated staff to continuously monitor, benchmark, and restore large HVAC systems to peak performance that would not be practical for the majority of residential buildings.
Solar-Enhanced Cooling System	○	n/a	(●)	0.05	The commercial study considered solar-enhanced cooling systems using both liquid-desiccant and absorption cycles. The economic benefit for this technology option can only be realized for large commercial applications, and would not offer a realistic payback for most residential buildings.
Solar Ventilation Preheating	×	n/a	●	0.11	This technology is most applicable for buildings with large, uninterrupted exterior walls and significant ventilation requirements, both of which are uncommon in residential buildings.

● - *Included in the in-depth analysis* (●) - *Included in the in-depth analysis, but combined into one entry*

○ - *Considered in the study but was screened out* × - *Not considered in the study* *n/a – Not Available*

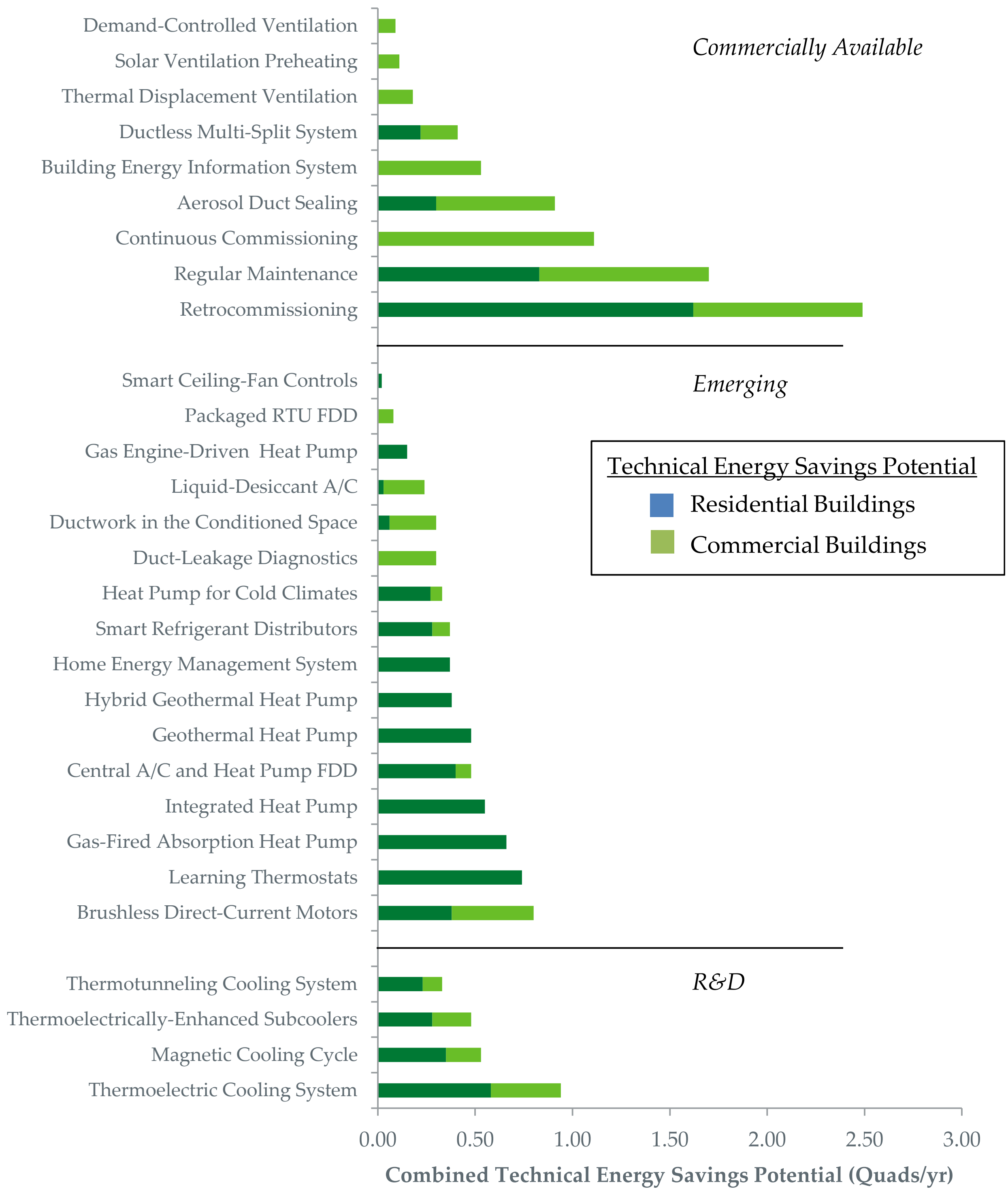


Figure 5-3. Combined Technical Energy Savings Potential for Residential and Commercial Priority Technology Options

The residential and commercial studies identified the early-stage technology options listed in Table 5-5. Some of the early-stage technology options identified in each study differ because:

- Certain technology options are applicable only to commercial buildings, i.e., DEVap A/C, nanofluid refrigerant additives, thermoelectrically enhanced radiators, zephyr ceiling tiles, and are not applicable to the residential sector.
- During the literature search performed for the residential study, we uncovered technology options that were not identified during the commercial study. These technology options may have applications for both residential and commercial HVAC systems once fully developed.

Table 5-5. Combined List of 14 Early-Stage Technology Options

Early-Stage Technology Option	
Commercial Study Only	**Residential Study Only**
Desiccant-Assisted Evaporative Air Conditioner (DEVap A/C)	Active Modular Phytoremediation Wall
Nanofluid Refrigerant Additives	Advanced Membrane Heat Pump
Thermoelectrically Enhanced Radiators	Air-Bearing Heat Exchanger
Zephyr Ceiling Tiles	Binary Fluid Ejector
	Co-Fluid Vapor Compression
	Self-Cleaning Heat Exchanger
Commercial and Residential Study	
Bernoulli Heat Pump	
Metal-Foam Heat Exchanger	
Thermoelastic Cooling System	
Turbo-Compressor-Condenser-Expander	

5.4 Summary of Recommended RD&D Initiatives for Both Residential and Commercial HVAC

Based on our review of the priority technology options identified in both the residential study and the 2011 commercial study, we recommend that DOE and industry stakeholders pursue the RD&D initiatives outlined below. Because many of the residential and commercial priority technology options require similar RD&D initiatives, we present a combined list of recommendations.

We recommend that DOE, in conjunction with other stakeholders, take the lead role in supporting basic research and development of immature technology options, while manufacturers and industry organizations) take lead roles in demonstrating, refining, and supporting emerging and available technology options. While we recommend lead organizations for each recommended initiative, many of these initiatives will require collaboration among the various industry stakeholders, including homeowners and commercial building owners/operators.

5.4.1 Summary of Recommended DOE-Led Initiatives

Early-Stage Technology Options

Table 5-5 (above) identifies 14 technology options (for residential and commercial combined) in the early stages of R&D for which there was a paucity of publicly available information. These technology options may have significant potential, but need further evaluation to understand their applicability for residential and/or commercial HVAC systems. Because we were unable to credibly evaluate their energy savings potential, we recommend that DOE pursue the initiatives listed in Table 5-6.

Table 5-6. Summary of Recommended Initiatives for Early-Stage Technology Options (Combined List from Residential and Commercial Studies)

Early-Stage Technology Options	Recommended Initiatives	Applicable Market(s)
Active Modular Phytoremediation (AMP) System	• Monitor progress of the AMP prototype development at Rensselaer Polytechnic Institute and determine further actions based on prototype success.	Residential, Commercial
Advanced Membrane Heat Pump	• Monitor prototype development through ARPA-e- and DOD-funded projects at Dais Analytic Corporation. • Perform an investigative study to understand the humidification-heating capabilities of a reverse-driven system.	Residential, Commercial
Air-Bearing Heat Exchanger (ABHX)	• Monitor the development of next-generation prototypes at Sandia National Laboratory. • If successful, model the ABHX system for HVAC applications.	Residential, Commercial
Bernoulli Heat Pump	• Monitor prototype development through DOE-funded projects by Machflow Energy at Clark University.	Residential, Commercial
Binary Fluid Ejector	• Monitor prototype development by May-Ruben Technologies.	Residential, Commercial
Co-Fluid Vapor Compression	• Monitor prototype development through ARPA-e funded projects at the University of Notre Dame.	Residential, Commercial
Desiccant-Assisted Evaporative Air Conditioner (DEVap A/C)	• Continue to support prototype testing and component refinement at the National Renewable Energy Laboratory (NREL).	Commercial
Metal-Foam Heat Exchanger	• Perform an investigative study to understand the effects of corrosion, condensate, and particulates on metal-foam systems in practical environments. • If the study is favorable, perform an additional study on the applicability of metal-foam heat exchangers in HVAC applications.	Residential, Commercial
Nanofluid Refrigerant Additives	• Perform an investigative study to determine if nanofluids could reduce the energy consumption of HVAC systems. • Upon favorable study results, test nanoparticle combinations to determine most-promising nanofluid combinations.	Commercial
Self-Cleaning Heat Exchanger	• Investigate self-cleaning heat exchangers to determine their technical and economic viability for HVAC systems sized for residential applications.	Residential, Commercial
Thermoelastic Cooling System	• Monitor prototype development through ARPA-e-funded projects at University of Maryland and supported by Pacific Northwest National Laboratory (PNNL).	Residential, Commercial
Thermoelectrically Enhanced Radiators	• Perform thermodynamic modeling to evaluate the heat-transfer enhancement of this technology option and its effect on energy consumption.	Commercial
Turbo-Compressor-Condenser-Expander	• Monitor prototype development by Appollo Wind Technologies.	Residential, Commercial
Zephyr Ceiling Tiles	• Perform an investigative study to determine the viability of Zephyr Ceiling Tiles for U.S. office buildings.	Commercial

R&D Stage Technology Options

I. *Support development of advanced high-ZT and low-work-function materials for solid-state cooling applications*
Applicable Technology Options: Thermoelectric Cooling System, Thermoelectrically Enhanced Subcoolers, Thermotunneling Cooling System

The low efficiency of current thermoelectric and thermotunneling materials has been a major obstacle for the development of solid-state cooling systems. We recommend that DOE support research in basic material science and nano-scale engineering to advance material properties beyond the current capabilities of available materials. In this process, standardized testing methodologies should be developed to improve the repeatability and reproducibility of test results, and allow for proper comparison among material alternatives.

II. *Support development of designs reducing the use of rare-earth metals*
Applicable Technology Options: Magnetic Cooling Cycle, Thermoelectric Cooling System, Thermotunneling Cooling System, Thermoelectrically Enhanced Subcooler, Brushless Direct-Current Motors

Solid-state cooling systems and certain high-efficiency components, such as brushless direct-current motors, rely on expensive, rare-earth metals to power key magnetic components. We recommend that DOE support research of alternative designs that reduce or eliminate dependence on rare-earth metals while maintaining high efficiency.

III. *Support the development of prototypes for laboratory testing in capacities suitable for HVAC systems*
Applicable Technology Options: Metal-Foam Heat Exchangers, Thermotunneling Cooling System, Thermoelectrically Enhanced Subcoolers

Although researchers have achieved promising results through small-scale testing, these technology options require additional laboratory testing using prototypes sized closer to their future HVAC applications. For example, researchers have demonstrated potential energy savings and performance benefits for thermoelectrically enhanced subcoolers through limited laboratory testing of a small-capacity unit without parasitic loads. The effectiveness of these technology options relies on their ability to transfer heat under specific conditions, which may not be attainable in larger systems. By developing larger-scale prototypes, researchers can identify potential barriers to efficient performance relating to material manufacturability, auxiliary energy requirements, and size constraints. We recommend DOE support the development of larger-scale prototypes for various system designs and configurations to better recognize additional developmental requirements and evaluate the future potential for these advanced technology options.

IV. Support development of improved manufacturing strategies for small-scale, advanced-material technologies
Applicable Technology Options: Magnetic Cooling Cycle, Thermoelectric Cooling Cycle, Thermoelectrically Enhanced Subcooler, Thermotunneling Cooling Cycle, Metal-Foam Heat Exchangers, Brushless Direct-Current Motors

Technology options using novel materials and processes require new fabrication techniques to reduce production costs and increase commercial viability. For example, the manufacturing techniques currently used for solid-state cooling prototypes are based on semiconductor production strategies. Semiconductor production strategies, however, are not typically optimized for the intricate bonding and shaping techniques required by these technology options. Because these technology options use such novel materials and designs, non-optimized production methods can result in significant product variability, which slows product development. We recommend that DOE support research on alternative manufacturing strategies that accommodate the unique handling requirements of the advanced materials while maintaining tight tolerances. In addition, we recommend that DOE evaluate larger-scale manufacturing concepts, including projecting the ultimate cost of manufacturing products suitable for HVAC systems using these advanced materials.

Emerging and Commercially Available Technology Options

I. Conduct long-term field studies on alternative ventilation strategies for both commercial and residential applications
Applicable Technology Options: Demand-Controlled Ventilation, Thermal Displacement Ventilation

The alternative ventilation strategies of demand-controlled and thermal-displacement ventilation have been shown to save energy in certain commercial applications (particularly buildings having low occupancy during peak hours). While ventilation has traditionally not been a major consideration for residential HVAC systems, building codes requiring tighter envelopes and growing concerns about IAQ will increase the importance of efficient ventilation strategies within homes. Current literature suggests energy savings from alternative ventilation strategies can vary significantly depending on site-specific issues, and may not be suitable for all projects. To better understand the capabilities of these technology options, we recommend that DOE conduct field testing across a variety of locations, building types, and system designs. for both commercial and residential applications. The chosen buildings should undergo long-term monitoring to help quantify the energy savings, non-energy benefits relating to improved IAQ such as occupant productivity, comfort, and health, and identify potential issues such as sensor degradation. These field studies will help identify the most promising applications for alternative ventilation strategies and facilitate integration with building simulation software. Because we suspect changes in building codes, and concerns for IAQ will create a greater demand for residential ventilation systems in future years, we also recommend DOE conduct a more in-depth study analyzing how these changes will affect future home HVAC energy consumption.

II. *Support development of strategies to facilitate assessment of airflow and thermal efficiency of ducts*

Applicable Technology Options: Aerosol Duct Sealing, Duct-Leakage Diagnostics

HVAC duct leakage contributes to increased fan usage and wasted thermal energy in existing residential and commercial buildings, in which, until recent years, little emphasis was placed on careful duct design and installation. Strategies to quickly identify and remediate duct leakage are underdeveloped, especially for complex duct systems. Because it is prohibitively expensive to evaluate existing ductwork when the need for remediation is uncertain, we recommend that DOE conduct a study of the U.S. residential and commercial building stock to identify the characteristics of buildings most likely to benefit from duct sealing and insulation. We also recommend that DOE support development of standard test methodologies, sensor systems, and strategies for evaluating airflow and thermal efficiency in both residential and commercial duct systems.

III. *Conduct independent laboratory and field testing of intelligent controls and diagnostic technologies*

Applicable Technology Options: Central A/C and Heat Pump FDD, Home Energy Management System, Learning Thermostat, Smart Ceiling-Fan Controls, Smart Refrigerant Distributors

With the decreased cost of computing power in recent years, intelligent monitoring and control technology options have entered into the U.S. residential HVAC market. Many of these advanced technology options have features such as sensors, microprocessors, and wireless communications to automatically control the HVAC system's operating schedule or provide fault detection, and diagnostic capabilities. In theory, these systems could benefit single- and multi-family buildings by optimizing operations and maintaining efficient performance for HVAC systems. For example, a learning thermostat could adjust temperature set-points automatically based on occupancy patterns, saving energy when the home is unoccupied. But, because good field data are not available, the actual benefits and energy savings to the homeowner are uncertain. We recommend that DOE conduct independent testing, both in a controlled laboratory environment under idealized residential conditions and at field tests in homes, to investigate the potential for these technology options. The results of this testing would help determine if these intelligent systems achieve advertised capabilities.

IV. *Support further refinement of the energy economics for performance optimization and diagnostics technologies*

Applicable Technology Options: Building Energy Information System, Continuous Commissioning, Packaged Rooftop Unit FDD, Retrocommissioning, Home Energy Management Systems, Central A/C and Heat Pump FDD, Learning Thermostat, Regular Maintenance

Technology options that optimize performance and diagnose identified system faults have an enormous potential to reduce HVAC energy consumption. Nevertheless, energy savings can vary widely depending on whether a building's HVAC system is operating as designed or whether its performance has fallen off significantly over time. To help lower uncertainties about the benefits of these technology options, we recommend that DOE create a database of successful projects to demonstrate the capabilities of these strategies to building/homeowners, utilities, and others involved in the HVAC and building industry, including better projections of upfront costs, energy savings, and non-energy benefits.

V. Develop greater understanding of real-world energy performance for HVAC equipment and systems over their lifetime

Applicable Technology Options: Building Energy Information System, Continuous Commissioning, Packaged Rooftop Unit FDD, Retrocommissioning, Regular Maintenance, Central A/C and Heat Pump FDD

The operation and efficiency of an HVAC system often changes over the course of its useful life, and numerous strategies are available to maintain or improve the initial energy performance of the system. These technology options and strategies identify inefficiencies within HVAC systems by monitoring certain key indicators and benchmarking trends against expected performance levels. Understanding how equipment aging affects system operations and energy consumption leads to more accurate baseline performance and efficiency models. We recommend that DOE support research to better assess the real-world performance of HVAC systems as they age. The analysis should be based on operational data collected through both accelerated-life testing and long-term field testing of existing systems, and focus on specific equipment (e.g., a chiller rather than the entire cooling system) over its operational life. The results of this testing would correlate the effects that maintenance has on equipment energy consumption and expected operational duration. Understanding which system problems lead to decreased equipment lifetimes helps contractors and end users prioritize their maintenance strategies. The insights gained from this study could improve the benchmarking capabilities of performance optimization and diagnostics systems as well as establish baselines for lifetime building energy standards.

VI. Conduct long-term field testing of alternative and advanced heat-pump designs for heating applications

Applicable Technology Options: Gas-Fired Absorption Heat Pump, Gas Engine-Driven Heat Pump, Ductless Multi-Split System, Integrated Heat Pump, Heat Pump for Cold Climates

For many regions of the U.S., innovative heat-pump designs can provide significant primary energy savings over conventional fossil-fuel or electric heat-pump heating technology options. Despite their energy savings, these technology options typically have long payback periods due to their high upfront cost premiums. In many cases, these novel heat pumps are just emerging for the U.S. residential market, and do not have a strong history of reliable and efficient performance while offering an attractive payback to the homeowner. Because of this, both homeowners and contractors are less likely to select them, particularly if the technology significantly differs from conventional vapor-compression heat pumps (e.g., gas-fired absorption heat pump). We recommend DOE investigate the energy savings and performance of these alternative and advanced heat-pump technology options through field testing conducted over a number of years, at multiple sites located in various U.S. climate regions. The results of this testing would a) reveal the cost-effectiveness, reliability, and end-user acceptance of these technology options for different residential applications in the U.S., b) educate homeowners and the residential HVAC industry, and c) provide a better basis for wider commercialization.

VII. Develop cost-effective and reliable gas-fired heat-pump products for single-family residential applications
Applicable Technology Options: Gas-Fired Absorption Heat Pump, Gas Engine-Driven Heat Pump

The seasonal efficiency of conventional, fuel-fired, space-heating equipment is inherently limited to about 95%. Breaking the 100% efficiency barrier for gas-fired heating requires the use of a heat pump—either engine-driven vapor compression or absorption cycle. Although these technology options could save significant amounts of heating energy across much of the U.S., the current significant cost premiums and limited availability in capacities suitable for single-family homes contributes to their poor market acceptance. We recommend DOE support the development of cost-effective and reliable gas-fired heat pumps primarily designed for space heating of single-family homes. Establishing that these innovative technology options are viable for residential heating in the U.S. will help achieve more efficient utilization of natural gas and other fossil fuels.

VIII. Develop novel strategies and equipment to reduce the upfront cost of GHP systems
Applicable Technology Options: Geothermal Heat Pump, Hybrid Geothermal Heat Pump, Integrated Heat Pump, Ductless Multi-Split System

Although the upfront cost for geothermal heat pumps has declined in recent years due to contractor experience, increased manufacturer competition, and government incentive programs, these installations still carry a significant cost premium over conventional HVAC systems, limiting wider adoption. Further breakthroughs are needed to increase system efficiency and lower upfront costs by using high-efficiency components, alternative ground-loop designs, advanced drilling techniques, lower-cost site evaluation tools/techniques, and better design strategies. We recommend that DOE support the next generation of GHP technologies through evaluation of more cost-effective drilling methods and auxiliary components, such as pump motors, laboratory and field testing of promising system designs, development of integrated design simulation and life-cycle-cost estimation software, and promotion of advanced ground-loop designs and other novel strategies throughout the HVAC industry.

5.4.2 Summary of Recommended Manufacturer-Led Initiatives

I. Develop techniques for cost-effective integration of technology options into replacement equipment and existing HVAC systems
Applicable Technology Options: Smart Refrigerant Distributors, Thermoelectrically Enhanced Subcoolers, Brushless Direct-Current Motors, Home Energy Management System, Learning Thermostat, Aerosol Duct Sealing

Given the longevity of most residential and commercial buildings, replacement and/or retrofit of existing HVAC equipment is critical to achieving energy savings. We recommend that manufacturers investigate equipment designs and installation strategies that minimize the cost and inconvenience associated with replacing or retrofitting existing HVAC equipment.

II. *Conduct demonstrations of, and publish field data for, advanced components using a variety of equipment designs*
Applicable Technology Options: Smart Refrigerant Distributors, Thermoelectrically Enhanced Subcoolers, Smart Ceiling-Fan Controls

Uncertainties about reliability, cost, and energy savings are key barriers to the adoption of these technology options. We recommend that manufacturers conduct field demonstrations of these component technology options, retrofitted in existing equipment or as a component in replacement equipment, to establish their viability in the residential market.

III. *Optimize the capabilities and number of sensors for performance optimization and diagnostics systems*
Applicable Technology Options: Building Energy Information System, Continuous Commissioning, Packaged Rooftop Unit FDD, Retrocommissioning, Home Energy Management System, Central A/C and Heat Pump FDD, Learning Thermostat

Each of these technology options reduces energy consumption over time by utilizing sensors to monitor HVAC system operation and other conditions. We recommend that manufacturers develop strategies to transmit the necessary information more effectively at lower cost. For example, offering sensors with self-identifying capabilities that can automatically link multiple sensors over a wireless network can reduce installation costs. We also recommend that manufacturers determine which HVAC operating conditions are the leading indicators of inefficient performance, and then develop algorithms to provide the necessary monitoring and benchmarking capabilities using fewer sensors.

5.4.3 Summary of Recommended Industry Organization-Led Initiatives

I. *Incorporate duct-leakage prevention and best practices into future building standards and codes*
Applicable Technology Options: Aerosol Duct Sealing, Duct-Leakage Diagnostics

We recommend that industry organizations train HVAC technicians and building operators on the latest prevention, detection, and repair methods to address duct leakage in both new and existing buildings. We also recommend that industry organizations work with building code officials to create building codes that encourage placement of ducts in the conditioned space (without increasing building shell size) and duct-leakage testing upon installation of equipment, similar to California Title 24. Mandating duct-leakage testing and remediation for renovation projects through building codes would improve the performance for existing buildings. We also recommend that building certification programs, such as Leadership in Energy and

Environmental Design (LEED) or ENERGY STAR, award points in their ratings for benchmarking a building's duct leakage and taking steps to reduce the associated energy losses.

II. **Develop improved test procedures and rating methods**
Applicable Technology Options: Heat Pump for Cold Climates, Ductless Multi-Split System, Gas Engine-Driven Heat Pump, Integrated Heat Pump, Geothermal Heat Pump, Hybrid Geothermal Heat Pump

Some of the efficiency advantages of these technology options, such as optimized performance at part-load conditions, more efficient heating in cold weather, utilizing heat recovery, and/or primary energy savings through fuel switching, are often not captured by current equipment rating methods. Conversely, the performance ratings for some of these technology options can overrepresent system efficiency by failing to capture the energy consumption of auxiliary components or cycling losses, such as the pump motor for geothermal heat pumps. We recommend that industry organizations improve test procedures and rating methods to reflect real-world energy performance of advanced technologies as compared to more conventional systems.

III. Increase collaboration among the various industry organizations to promote advanced equipment integrating HVAC and water-heating technologies
Applicable Technology Options: Integrated Heat Pump, Gas Engine-Driven Heat Pump, Gas-Fired Absorption Heat Pump

Because residential buildings have significant water-heating loads, providing hot water using a heat pump or capturing waste heat from HVAC systems for water heating provides a significant opportunity to raise the utilization of primary energy for residential homes. Certain HVAC technologies have emerged with the capability to integrate space-conditioning and water-heating systems that require greater collaboration between the HVAC and plumbing industries to reach their full potential. We recommend the regulating bodies and other organizations across building industries, such as ASHRAE, AHRI, and ASPE cooperate and support these integrated technology options by conducting joint promotional activities, standardizing rating systems, and providing contractor training on best practices.

IV. Establish industry standards for fault detection and diagnostics systems
Applicable Technology Options: Building Energy Information System, Continuous Commissioning, Packaged Rooftop Unit FDD, Central A/C, and Heat Pump FDD

Fault detection and diagnostics systems identify system malfunctions or trends of poor efficiency, and alert occupants or maintenance personnel of the need for maintenance. Although various FDD methods exist, we recommend that industry establish common terminology and standards for fault thresholds to facilitate interoperability across the HVAC industry. The success of FDD systems, especially for commercial packaged and residential split-system equipment, depends on eliminating potential false alarms and easily identifying faults. Creating these standards allows field technicians to identify and repair faults more quickly, and increases compatibility across the multiple levels of automated systems and controls. Common terminology fosters industry-wide understanding of FDD's benefits and capabilities while providing a platform to share best practices.

5.4.4 Summary of Recommended Utility Initiatives

I. ***Offer incentives to decrease the upfront costs of performance optimization and diagnostics systems***
Applicable Technology Options: Building Energy Information System, Continuous Commissioning, Packaged Rooftop Unit FDD, Retrocommissioning, Aerosol Duct Sealing, Regular Maintenance, Central A/C, and Heat Pump FDD

Gas and electric utilities offer incentive programs that reduce the upfront costs of energy-saving technologies. To advance these technology options, we recommend that utilities offer incentives to offset the incremental cost of equipment containing FDD capabilities, or the upfront cost of an initial retrocommissioning study and other performance optimization strategies.

II. ***Promote alternative and advanced heat-pump designs through commercialization and incentive programs***
Applicable Technology Options: Heat Pump for Cold Climates, Ductless Multi-Split System, Geothermal Heat Pump

Many high-performance heat-pump technologies have considerable cost premiums and long payback periods when compared to conventional HVAC equipment, slowing the adoption of these technology options. These alternative and advanced heat-pump designs offer significant potential for peak-demand reduction and overall energy savings across a utility's service territory. We recommend that utilities incorporate these heat-pump technology options into demand-side management programs and promote wider adoption through commercialization initiatives. Proving the effectiveness of the technology options through field testing within the service territory may increase customer acceptance.

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U.S. EIA. 2011. "2009 Residential Energy Consumption Survey." U.S. Energy Information Administration. October 2011.

Appendix A List of the Initial 135 Technology Options

Components (36)	Equipment (56)
Additives for Liquid Friction Reduction	Adsorption Cooling System
Advanced Defrost Methods for Heat Pumps	Advanced Evaporative Coolers
Advanced Fan Designs	Advanced Membrane Heat Pump
Advanced HVAC Sensors	Aerodynamic Condensing Units
Air-Bearing Heat Exchanger	Basic Evaporative Cooling
Ambient Subcoolers	Bernoulli Heat Pump
Binary Fluid Ejector	Biomass Furnaces and Boilers
Brushless Direct-Current Motors	Brayton Cycle Heat Pump
Electrochemical Heat Pump	Chemical Water Treatment
Electronic Expansion Valves	Chilled Water Economizer
Enhanced Heat Transfer for Heat Exchangers	Co-Fluid Vapor Compression
Heat Pipe Dehumidification System	Coil-less, Electric Tankless Water Heater for Radiant
HFO Refrigerants	Condensing Fireplace
High-Efficiency Circulator Pumps	Condensing Furnaces and Boilers
High-Efficiency Gas Burners	Cromer Cycle Air Conditioning
Hot-Gas Bypass	Desuperheater for Water Heating
Hydrocarbon/Natural Refrigerants	Dual Compressor Chillers
Improved Insulation for Distribution Systems	Dual-Fuel Heat Pump
Inverter-Driven Compressors (Variable-Speed Drives)	Ductless Multi-Split System
Low-Friction Piping	Ejector Heat Pump
Mechanical Subcooler	Electron-Beam Water Treatment
Metal-Foam Heat Exchanger	Electrostatic Water Treatment
Microchannel Heat Exchanger	Evaporatively Cooled Condensers
Optimized Heat Exchanger Design	Gas Engine-Driven Heat Pump
Polymer-Metal Hybrid Heat Exchanger	Gas-Fired Absorption Heat Pump
Pulse Combustion Furnaces and Boilers	Geothermal Heat Pump
Screw Compressor with Vapor Injection	Heat Pump for Cold Climates
Self-Cleaning Heat Exchanger	Hot-Dry Air Conditioner
Smaller Centrifugal Compressors	Hybrid Chillers

Smart Refrigerant Distributors	Hybrid Geothermal Heat Pump
Staged Compressors	Hybrid Tankless/Storage Water Heater
Swing/Rolling Piston Compressors	Integrated Heat Pump
Thermoelectrically Enhanced Subcoolers	Liquid-Desiccant Air Conditioner
Thermostatic Regulator Valves	Magnetic Cooling System
Twin-Single Compressors	Micro-Combined Heat and Power
Variable-Stroke Compressor	Modular Chillers and Boilers
Distribution Systems (31)	Modulating Furnace
3D BIM / Energy Modeling	Nighttime Ventilation Cooling
Active Air Filtration to Reduce Outdoor Air Requirement	Ozone Water Treatment
Active Modular Phytoremediation Wall	Reduced Air-Handler Unit Cabinet Leakage
Active Thermal Energy Storage	Smart Ceiling-Fan Controls
Active Window Insulation	Smart Ventilation Systems
Air-Ground Heat Exchanger	Solar Water Heating
Airflow-Optimizing System	Solar-Enhanced Absorption Chiller
Attic Radiant Barrier	Solar-Enhanced Vapor-Compression Systems
Attic Venting	Tankless Water Heater for Radiant
Chilled-Beam Radiant Cooling	Thermoacoustic Cooling System
Daylighting Strategies	Thermoelastic Cooling System
Dedicated Dehumidification System	Thermoelectric Cooling System
Ductwork in the Conditioned Space	Thermotunneling Cooling System
Evaporative Roof Cooling	Transport Membrane Condenser
High Performance Windows (U<0.25)	Turbo-Compressor-Condenser-Expander
High Quality Building Insulation	Unitary Thermal Storage System
High-Sidewall Diffusers for Transient Air Mixing	Vortex Tube Cooling System
Improved Duct Systems	Vuillimier Heat Pump
Improved Zone Control	Water-Cooled Condensers for Unitary Equipment
Microenvironments	**Installation, Operations and Maintenance (7)**
Mixed-Mode Conditioning	Aerosol Duct Sealing
Net Zero Energy Design	Central A/C and Heat Pump Fault Detection and Diagnostics
Night Sky Radiant Cooling	Continuous Commissioning
Passive Thermal Energy Storage with Phase Change Materials	Multilevel Fault Detection and Diagnostics

Residential Cool-Color Roofing	Quality Installation
Seasonal Thermal Energy Storage	Regular Maintenance
Shading Condenser Coils	Retrocommissioning
Small Duct, High-Velocity System	**Controls, Behavior Modification (3)**
Swimming-Pool Heat Sink	Home Energy Management System
Using North/South Facing Heat Exchangers	Learning Thermostat
Zero-Maintenance Design	Submetering
Community-Based Systems (2)	
Connectivity with Smart Meter and Grid	
District Heating and Cooling	

Appendix B List of Resources Used in Literature Search

Resource Name	Acronym	Method	Notes
Industry Organizations/Publications			
Air-Conditioning, Heating and Refrigeration Institute	AHRI	Review of Titles/Abstracts	
Air-Conditioning, Heating and Refrigeration Technology Institute	AHRTI	Review of Titles/Abstracts	
Air Conditioning, Heating, and Refrigeration NEWS	ACHR	Targeted Keyword Search	Articles, product showcases, coverage of industry expos
American Society of Heating, Refrigerating and Air-Conditioning Engineers	ASHRAE	Both	Database of research projects, ASHRAE Journal (2007-current), AHR Expo and Conferences (2008-current)
International Journal of HVAC&R Research		Review of Titles/Abstracts	2006-current
Japan Air Conditioning, Heating, & Refrigeration News	JARN	Targeted Keyword Search	Articles, product showcases, coverage of industry expos
Association of Energy Engineers	AEE	Review of Titles/Abstracts	
American Council for an Energy-Efficient Economy	ACEEE	Review of Titles/Abstracts	Research reports and Summer Studies on Energy Efficiency in Buildings (2000-current)
Consortium for Energy Efficiency	CEE	Review of Titles/Abstracts	
National Institute of Building Sciences	NIBS	Review of Titles/Abstracts	
International Association of Certified Home Inspectors	InterNACHI	Review of Titles/Abstracts	
Southwest Energy Efficiency Project	SWEEP	Review of Titles/Abstracts	
New Buildings Institute	NBI	Review of Titles/Abstracts	
Heating/Piping/Air Conditioning Engineering	HPAC	Targeted Keyword Search	Articles, product showcases, coverage of industry expos
Journal of Enhanced Heat Transfer		Review of Titles/Abstracts	2001-current
American Society of Mechanical Engineers	ASME	Review of Titles/Abstracts	Journal of Heat Transfer (2003-present)
National Association of Home Builders	NAHB	Targeted Keyword Search	Articles, product showcases, coverage of industry expos
Appliance Magazine		Review of Titles/Abstracts	Articles (2008-current)

Electric Power Research Institute	EPRI	Targeted Keyword Search	
Institute of Electrical and Electronics Engineers	IEEE	Targeted Keyword Search	IEEE Xplore
Building Science Corporation		Review of Titles/Abstracts	
Clean Technologies and Sustainable Industries Organization	CT-SI	Targeted Keyword Search	Articles, coverage of expos
Building America Program		Review of Titles/Abstracts	
Building Industry Research Alliance	BIRA	Review of Titles/Abstracts	
Fraunhofer Institute		Review of Titles/Abstracts	
International Journal of Energy Research		Review of Titles/Abstracts	2001-2009
International Air-Conditioning, Heating, Ventilation and Refrigeration Exhibition		Both	Climatizacion 2011 product showcase
International Trade Fair for Refrigeration, Air Conditioning, Ventilation and Heat Pumps		Both	Chillventa 2011 product showcase
Government Organizations and National Labs			
DOE Information Bridge		Targeted Keyword Search	
EERE: Energy Savers		Review of Titles/Abstracts	Solar Decathlon (2007-2011)
Brookhaven National Lab	BNL	Both	Database of research projects and publications
Oak Ridge National Lab	ORNL	Both	Database of research projects and publications
Pacific Northwest National Lab	PNNL	Both	Database of research projects and publications
Lawrence Berkley National Lab	LBNL	Both	Database of research projects and publications
Sandia National Lab		Both	Database of research projects and publications
National Renewable Energy Lab	NREL	Review of Titles/Abstracts	
National Energy Technology Lab	NETL	Review of Titles/Abstracts	
New York State Energy Research and Development Authority	NYSERDA	Review of Titles/Abstracts	
Small Business Innovation Research	SBIR	Targeted Keyword Search	Project awards through DOE
California Energy Commission	CEC	Both	Public Interest Energy Research (PIER) Program, database of research projects and publications

ENERGY STAR		Targeted Keyword Search	
Federal Rulemakings for Appliance Efficiency Standards			Technical Support Documents (TSDs) for central air-conditioners and heat pumps, dehumidifiers, furnace fans, furnaces and boilers, room air-conditioners, small duct - high velocity air-conditioners, water heaters
National Research Council - Canada	NRC	Review of Titles/Abstracts	
Natural Resources Canada	NRCAN	Review of Titles/Abstracts	
International Energy Agency	IEA	Both	Heat Pump Centre, Heat Pump Conference (2002-2011)
Japan Society for the Promotion of Science	JSPS	Both	Database of research projects and publications
New Energy and Industrial Technology Development Organization	NEDO	Both	Database of research projects and publications
Federation of European Heating, Ventilation and Air Conditioning Associations	REHVA	Both	REHVA European HVAC Journal, seminar presentations, project abstracts
European Commission on Research and Technology		Both	
Advanced Research Projects Agency - Energy	ARPA-e	Review of Titles/Abstracts	Technology showcases
Universities			
University of California - Davis	UC Davis	Review of Titles/Abstracts	Western Cooling Efficiency Center
University of Maryland	UMD	Review of Titles/Abstracts	Energy Research Center
University of Illinois		Review of Titles/Abstracts	Air Conditioning and Refrigeration Center
Purdue University		Review of Titles/Abstracts	International Compressor Conference, International Refrigeration and Air Conditioning Conference (2002-2010)
University of Wisconsin		Review of Titles/Abstracts	
University of Central Florida	UCF	Review of Titles/Abstracts	Florida Solar Energy Center
Massachusetts Institute of Technology	MIT	Review of Titles/Abstracts	MIT House_n
University of California - Berkeley	UC Berkeley	Review of Titles/Abstracts	Center for the Built Environment
Carnegie Mellon University	CMU	Review of Titles/Abstracts	Center for Building Performance and Diagnostics
Syracuse University		Review of Titles/Abstracts	Center of Excellence

Manufacturers			
GE	Sanyo	ECR International	United Technologies/Carrier
Daiken/McQuay	Greenheck	Dunkirk Boiler	Lennox
Honeywell	Unico	EMI	Samsung
Johnson Controls/York	Hudson	Peerless	Mestek
Mitsubishi	Ebm-pabst	Emerson	Robur
LG	Colmac	Ductsox	Goodman
Danfoss	Aeroseal	Multistak	Nordyne
Ingersoll Rand/Trane	Rheem	IceEnergy	

Appendix C Abridged Analyses of the 10 Early-Stage Technology Options

As discussed in Section 4, we performed an abridged analysis of 10 early-stage technology options for which there was a paucity of publicly available information because of their development status. This appendix consists of abridged analyses for those 10 technology options at an early stage of its development, including:

- Active Modular Phytoremediation Wall
- Advanced Membrane Heat Pump
- Air-Bearing Heat Exchanger
- Bernoulli Heat Pump
- Binary Fluid Ejector
- Co-Fluid Vapor Compression
- Self-Cleaning Heat Exchanger
- Thermoelastic Cooling System
- Turbo-Compressor-Condenser-Expander

Each abridged analysis provides a description of each technology, its development status, and its potential applications. We recommend that the DOE monitor the development of these technology options.

C.1 Active Modular Phytoremediation System

Brief Description	The Active Modular Phytoremediation (AMP) System is a ventilation system using hydroponic plant roots to remove toxins from the air.	
Attribute	**Value**	**Comments**
Systems Impacted	Air-distribution systems	
Annual Energy Consumption of Baseline Technology	4.06 Quads/yr	We assume all HVAC energy consumption could be affected by the AMP system and 50% of all homes could use this system.
Non-Energy Benefits	Improved Air Quality	

Description of Technology

The AMP System is a biomechanical filtration system that improves indoor air quality. AMP uses plants in a hydroponic wall system to remove toxins, such as volatile organic compounds (VOCs), from the air. The hydroponic system exposes the plants roots, allowing air to flow over the rhizosphere, or areas immediately surrounding the roots. A series of fans circulate air over the plant's rhizosphere, removing toxins more efficiently than plant leaves or the roots themselves (Note: the rhizosphere does not include the actual roots), according to Anna Dyson (2011), one of the system's creators. The fans direct filtered air to the building's HVAC system for distribution throughout the building.

The modular design of the AMP allows for easy adaptation to a wide variety of buildings, from small residential to large-commercial facilities.

Technical Maturity and Recent Developments

This technology is not commercially available and further research is ongoing.

The Spark Award (Dyson 2011) summary states that CASE, the Center for Architecture Science and Ecology, is testing the performance of a prototype AMP system at Rensselaer's Aerosols Research Lab. CASE is developing additional prototypes to improve performance and installation flexibility.

From Inside Rensselaer (2010), "The AMP system is scheduled to be installed in the in Public Safety Answering Center II (PSAC II), a Bronx emergency-response center scheduled to open within the next five years."

Next Steps for Technology

CASE plans to install a prototype of the system at the PSAC II, which will provide a real-world assessment. We recommend monitoring the CASE AMP prototype progress and determining further actions based on prototype success.

References

Dyson, Anna. 2011. "Active Modular Phytoremediation System (AMPS)." '11 Spark Awards: Concept Entries. Retrieved from http://www.sparkawards.com/Galleries/11_Concept_Entries.htm?appid=4320.

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C.2 Advanced-Membrane Heat Pump

Brief Description	Driven by a compressor, advanced-membrane heat pumps provide cooling/dehumidification and/or heating/humidification by transferring moisture across a number of membranes.	
Attribute	**Value**	**Comments**
Systems Impacted	Conventional air conditioners and heat pumps	
Annual Energy Consumption of Baseline Technology	1.53 Quads/yr	Central air conditioners and heat pumps, medium replacement potential.
Non-Energy Benefits	No refrigerants, improved IAQ and comfort	

Description of Technology

Emerging research in material science and nanotechnology has led to the development of selectively permeable membranes that transport water molecules across their surface very efficiently while inhibiting the migration of air. Already commercialized for water purification and enthalpy heat-recovery units, the capabilities of the membranes could supply high-efficiency dehumidification and cooling (or humidification/heating if the cycle is reversed). Figure C.2-1 provides a schematic of the cooling process for an advanced-membrane heat pump.

- Warm, humid air passes across a dehumidifier (1) lined with the membrane. The compressor (2) creates a partial vacuum across the dehumidifier membrane that removes moisture from the airstream.
- After leaving the dehumidifier, the warm, dry air passes over a heat exchanger (3) cooled by a chilled-water loop and enters the conditioned space.
- A chiller (4), consisting of a water channel lined with the membrane, cools the water loop by evaporating a portion of the water. The compressor (2) creates a partial vacuum that evaporates a portion of the liquid water as it travels across the membrane.
- The compressor (2) collects the water vapor from the dehumidifier (1) and chiller (4), and expels it to the atmosphere through the expirator (5).

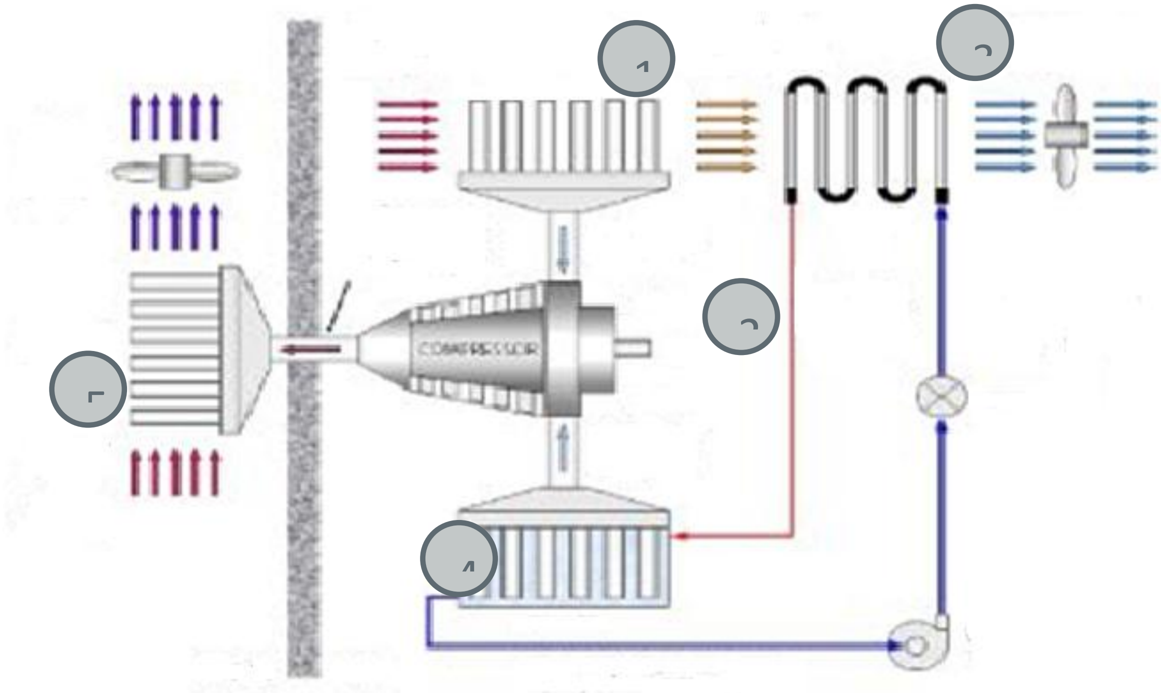

Figure C.2-1. Advanced Membrane Cooling Process

Source: EE&T (2011)

Technical Maturity and Recent Developments

Researchers at Dais Analytic have received research grants through ARPA-e and the Department of Defense to demonstrate the capabilities of their Aqualyte membrane for HVAC applications. They have demonstrated a 0.5-ton prototype, and are currently developing and testing a larger prototype. The company hopes to partner with HVAC manufacturers to commercialize the membrane and heat exchangers of the NanoAir system for use in OEM product offerings.

Next Steps for Technology

The NanoAir system requires additional R&D efforts to bring the technology to further maturity including 3rd-party performance testing. Optimizing the controls of the dehumidifier and chiller is needed demonstrate the system's capabilities in various climate regions. Further investigation is needed to understand the humidification-heating capabilities of a reverse-driven system.

References

Dais Analytic. 2011. "Dais Analytic Corporation – NanoAir Overview July 2011." Retrieved from http://www.youtube.com/watch?v=2AvA45vrBvc.

EE&T. 2011. "DOE Takes a Look at Refrigerant-Free A/C." Energy Efficiency & Technology. March 2, 2011.

Ehrenberg, Scott. 2011. Personal Communication. December 22, 2011. Dais Analytic Corp.

C.3 Air-Bearing Heat Exchanger

Brief Description	The air-bearing heat exchanger uses a rotating, bladed heat sink separated by a small gap of air to reduce the boundary layer in a condenser or evaporator heat exchanger.	
Attribute	**Value**	**Comments**
Systems Impacted	Air Conditioners and Heat Pumps	
Annual Energy Consumption of Baseline Technology	3.06 Quads/yr	
Non-Energy Benefits	Noise Reduction	

Description of Technology

Dr. John Koplow (2010) describes the Air-Bearing Heat Exchanger (ABHX) as an alternative heat exchanger to traditional fans, fins and heat sinks for electronics-cooling applications. The ABHX rotates a flat, bladed heat sink using a brushless motor, mounted on the flat base plate. The base plate and heat sink are separated by a small air gap--a hydrodynamic gas bearing--which has low thermal resistance due to high shear. The bladed heat sink rotates at several thousand RPM, providing the violent shearing of the air gap, reducing the boundary layer by up to a factor of 10, and significantly reduces heat-exchanger fouling.

Koplow (2010) claims the ABHX, if applied to HVAC, would reduce HVAC energy consumption in two ways:

- Reducing the boundary layer on the heat exchanger increases heat transfer, thus, increasing efficiency.
- Eliminating heat-exchanger fouling prevents a loss of 17% of cooling capacity and a 27% reduction in efficiency.

Technical Maturity and Recent Developments

This technology is not commercially available, and there are a few significant technical issues that will require long-term R&D efforts to address, as discussed below.

Koplow invented the ABHX in 2007, and began developing the device in 2009 for electronics-cooling applications Bartlett 2011). Koplow completed the first prototype in 2010 for CPUs, and mentions in his white paper (Koplow 2010) work starting on additional prototypes for computer applications.

Koplow has suggested the use of the ABHX for HVAC applications, but has not demonstrated ABHX in HVAC applications. Other areas being researched include ABHX vibrations (for CPU and possibly HVAC applications), design optimization (fin size, number of fins, optimal material), and adapting to other applications other than computer cooling.

Next Steps for Technology

Koplow is creating second and third-generation prototype ABHX's for computer applications at Sandia National Laboratories. Koplow's next steps include analyzing costs of the ABHX and optimizing the design. We recommend monitoring the next-generation prototypes, and upon successful demonstration, model the ABHX system for HVAC applications.

References

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Koplow, Jeffery. 2010. "A Fundamentally New Approach To Air-Cooled Heat Exchangers." January, 2010. Retrieved fromhttp://prod.sandia.gov/techlib/access-control.cgi/2010/100258.pdf.

Sebastian, Anthony. 2011. "The Fanless Spinning Heatsink: Your Questions Answered by the Inventor" ExtremeTech. July, 2011. Retrieved from http://www.extremetech.com/computing/90272-the-fanless-spinning-heatsink-your-questions-answered-by-the-inventor/2.

C.4 Bernoulli Heat Pump

Brief Description	Bernoulli heat pumps centrifugally accelerate a working fluid through a spinning nozzle to produce cooling. The working fluid, consisting of a mixture of noble gasses, changes temperature as it's accelerated through a Venturi nozzle.	
Attribute	**Value**	**Comments**
Systems Impacted	Vapor-compression A/C and heat pump systems	
Annual Energy Consumption of Baseline Technology	1.74 Quads/yr	Applicable for all cooling, medium replacement potential.
Non-Energy Benefits	Uses natural refrigerants	

Description of Technology

Bernoulli heat pumps use mixtures of noble gases (e.g., neon, krypton, xenon) to move heat from one source to another. Instead mechanically compressing the working fluid to cause variations in temperature, Bernoulli heat pumps centrifugally accelerate the working fluid through a Venturi nozzle. When the working fluid enters the nozzle, its cross-sectional area decreases, increasing its velocity. This energy conversion from random molecular motion to directed flow reduces the temperature and pressure of the working fluid, creating a usable temperature gradient. The same cooling effect is achieved whether gas is drawn through a stationary or rotating nozzle. This invention not only takes advantage of the Bernoulli principle, but also of the unusual thermodynamic transport properties of noble gases, also studied for thermoacoustic refrigeration.

Without the use of a compressor, Bernoulli heat pumps are driven by the motion of the working fluid through the Venturi-shaped duct. Depending on the configuration, the system would require a blower to move the working fluid and/or a motor to rotate one or a bank of nozzles. The Bernoulli heat pump could achieve comparable cooling performance without the use of HCFC or HFC refrigerants.

Technical Maturity and Recent Developments

Machflow, a small business associated with Clark University, produced a prototype Bernoulli heat pump. The company has also filed eight patents regarding this technology, and has received a Department of Energy grant to continue research in the area (Clark News Hub 2010).

Next Steps for Technology

Continued research on Bernoulli heat pumps is needed to identify appropriate working fluids and develop a field-ready prototype with the capacity, performance, and efficiency on par with conventional systems.

References

Clark News Hub. 2010. "Clark Physicist's Green Cooling Tech Startup Gets $1M Stimulus Grant." Clark University. September 1, 2010. Retrieved from http://news.clarku.edu/news/2010/09/01/clark-physicist%E2%80%99s-green-cooling-tech-startup-gets-1m-stimulus-grant/.

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Williams and Agosta. 2011. "Centrifugal Bernoulli Heat Pump." U.S. Patent No.: US 7,918,094 B2. April 5, 2011.

C.5 Binary-Fluid Ejector

Brief Description	The binary-fluid ejector is specifically designed for two fluids. One fluid optimizes refrigeration efficiency, while the other optimizes the ejector efficiency.	
Attribute	**Value**	**Comments**
Systems Impacted	Air Conditioners and Heat Pumps	
Annual Energy Consumption of Baseline Technology	0.21 Quads/yr	
Non-Energy Benefits	Fuel flexibility	

Description of Technology

The binary-fluid ejector concept pumps a refrigerant mixture through an ejector to replace the electromechanical compressor system of typical air conditioners and heat pumps. This binary-fluid ejector (BFE) has no moving parts, and the inventor, May-Ruben Technologies, claims it can use almost any source of thermal energy as fuel (e.g. solar, waste heat, and fossil fuel).

Technical Maturity and Recent Developments

This technology is not commercially available and requires significant development for commercialization.

May-Ruben Technologies (2012) has submitted U.S. and PCT (Patent Cooperation Treaty) patent applications for the binary-fluid ejector. They have also done preliminary analysis on potential binary fluids and believe HFE-7500 (a 3M product) and water are best suited for the technology.

May-Ruben (2012) plans to model the binary-fluid ejector and create a prototype to confirm their analysis. The first prototype will focus on distillation, and they plan to complete it in the fall of 2013.

Next Steps for Technology

We recommend performing an investigative study of the binary-fluid ejector for HVAC applications.

References

May-Ruben Technologies. 2012. "Binary-Fluid Ejector." Retrieved from http://www.may-rubentechnologies.com/index.php?option=com_content&view=article&id=64&Itemid=115.

C.6 Co-Fluid Vapor Compression

Brief Description	A heat pump utilizing a two-phase co-fluid can provide space conditioning by controlling heat transfer as an ionic liquid absorbs/desorbs CO_2.	
Attribute	**Value**	**Comments**
Systems Impacted	Conventional air conditioners and heat pumps	
Annual Energy Consumption of Baseline Technology	1.74 Quads/yr	All cooling systems, medium replacement potential.
Non-Energy Benefits	Uses natural refrigerants	

Description of Technology

Co-fluid vapor-compression systems can provide high-efficiency space conditioning utilizing the unique chemical properties of a low-GWP, dual-fluid refrigerant. Unlike conventional refrigerants, a co-fluid system transfers heat through the interaction between an ionic fluid and carbon-dioxide gas. Comprised of large salt molecules, ionic fluids can absorb CO_2 gas under pressure and remain a liquid under normal operating conditions. Each ionic liquid has a specific enthalpy of solvation that releases heat when it absorbs CO_2. Although compression of a two-phase fluid is difficult, a scroll compressor can drive the heat-transfer process to produce both heating and cooling (Spauschus et al. 2000):

- A scroll compressor elevates the pressure of co-fluid of gaseous CO_2 and ionic liquid
- As the resorber/condenser rejects heat from the co-fluid, gaseous CO_2 at least partially dissolves into the liquid co-fluid
- An expansion device reduces the pressure of the co-fluid, reducing the temperature of the co-fluid mixture.
- The lower pressure reduces the boiling point of the CO_2, which evaporates from the co-fluid by absorbing heat from the surroundings in the desorber/evaporator.

This high-efficiency co-fluid system allows for a CO_2-based refrigeration cycle at pressures much lower than a transcritical CO_2 cycle, on the order of 20 compared to 100 bar for a transcritical cycle. The nature of the ionic fluid determines the amount of CO_2 absorbed/desorbed by the co-fluid, and the resulting cooling capacity per unit mass flow.

Technical Maturity and Recent Developments

A team from the University of Notre Dame developed a number of ionic liquids suitable for co-fluid vapor compression. Through computer modeling based on previous research with CO_2 refrigeration cycles, the team identified ionic liquids that achieved COPs of 8-9 over a range of pressures (Schnieder 2011). The Notre Dame team received funding through the DOE's ARPA-e initiative to improve building efficiency. This research builds on previous DOE-sponsored work at Notre Dame developing ionic liquids for carbon capture and sequestration. In 2012, the team will conduct laboratory testing on a 1-ton transcritical CO_2 system with various co-fluid pairings to validate their computational models and drive future work.

Next Steps for Technology

The two largest issues to overcome with this technology relate to the two-phase nature of the co-fluid. Raising the pressure of the co-fluid is problematic because most compressors fail when exposed to a two-phase mixture. Although scroll compressors have worked during limited testing, this will be a major challenge for the development of a reliable commercial product. Researchers note that, if two-phase compression is unreliable, future prototypes may separate the two-stage mixture, compress the vapor and pump the liquid, and recombine the co-fluid before the resorber/condenser.

Development of this technology will focus on validation of modeled performance through laboratory testing, identification of promising co-fluids, and refinement of specific system components, primarily the compressor.

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C.7 Metal-Foam Heat Exchangers

Brief Description	Metal-foam heat exchangers use porous metal to allow a working fluid to pass through, increasing surface area and turbulent flow to improve heat transfer.	
Attribute	**Value**	**Comments**
Systems Impacted	Furnaces and Boilers	
Annual Energy Consumption of Baseline Technology	3.79 Quads/yr	
Non-Energy Benefits	None	

Description of Technology

Metal-foam heat exchangers use advanced porous metals to increase heat-transfer surface area. Metal-foam fills the space inside tubular, or between plate, heat exchangers, and the working fluid passes through the porous metal foam, exchanging heat. As the fluid passes through the foam, the individual metal strands promote turbulence, increasing heat transfer. The foam can be annealed and compressed to further raise HX density, but with a higher pressure drop. In addition to improving heat-transfer rates, metal-foam heat exchangers can lower fan energy consumption and reduce material usage when improving or replacing finned-tube heat exchangers in air conditioners and heat pumps. The metal foam can take the place of metal fins for fin-and-tube HXs with greater capacity and less material. Metal-foam heat exchange materials are currently being developed primarily for power electronics, but HVAC applications, fuel cells, and industrial processes are being considered.

Technical Maturity and Recent Developments

This technology is not commercially available and still requires some R&D efforts. No proof-of-concept testing has occurred for HVAC systems. AHRTI (2010) is supporting a project that will examine the HVAC applications of metal-foam heat-exchange materials, determine material safety, and develop component-level models for performance.

Next Steps for Technology

Additional research and testing is needed to develop metal-foam HXs for use in HVAC systems. Little is known of the effects of corrosion, condensate, and particulates on metal-foam systems in practical environments over time, especially with exposure to condensate in evaporators and outdoor or dusty conditions. Residential HVAC applications have not been demonstrated for metal-foam heat exchangers. Metal-foam heat exchangers require study on the HVAC applicability of metal-foam heat exchangers and a prototype for testing.

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C.8 Self-Cleaning Furnace Heat Exchanger

Brief Description	The self-cleaning furnace heat exchanger uses turbulent flow or brushes to remove scaling from heat-exchanger surfaces.	
Attribute	**Value**	**Comments**
Systems Impacted	Oil/Gas Furnaces	
Annual Energy Consumption of Baseline Technology	2.53 Quads/yr	
Non-Energy Benefits	Reduced maintenance	

Description of Technology

Two separate options for self-cleaning heat-exchanger technologies can descale the heat-exchanger surface to reduce fouling and improve efficiency.

A boiler and heat exchanger manufacturer, Triangle Tube, has a brazed-plate heat exchanger (shown in Figure C.8-1), which consists of plates that are brazed together, with every plate turned 180 degrees to create two flow channels with two mediums in counter current. This results in turbulent flow for higher efficiency and greater resistance to scaling.

Figure C.8-1. Sample Self-Cleaning Heat Exchanger

Source: TriangleTube (2011)

D.G. Klaren (2005), founder of Klaren BV in the Netherlands, created a heat exchanger used by commercial furnace manufacturers using a fluidized bed to remove scaling. The design uses cut metal wires (2-3mm) to scour mildly both the shell side and tube side of the heat exchanger. The particles also create a moderately turbulent flow to improve efficiency.

Technical Maturity and Recent Developments

This technology is commercially available for commercial-scale furnaces and water heaters; however, the self-cleaning furnace heat exchanger has not yet been adapted for residential

HVAC applications. A literature search did not identify evidence of development for residential HVAC applications.

Next Steps for Technology

We recommend performing a study to determine if a self-cleaning furnace heat exchanger for residential applications is viable and cost-effective.

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C.9 Thermoelastic Cooling System

Brief Description	Using the unique properties of smart-memory alloys (SMA), thermoelastic cooling systems twist and release a SMA core that absorbs heat from its surroundings.	
Attribute	**Value**	**Comments**
Systems Impacted	Conventional air conditioners and heat pumps	
Annual Energy Consumption of Baseline Technology	1.74 Quads/yr	All cooling systems, medium replacement potential.
Non-Energy Benefits	No refrigerants	

Description of Technology
Through the deformation of a smart-memory alloy (SMA), thermoelastic cooling devices could replace conventional, compressor-driven systems for residential air conditioning because of the unique properties of the SMA materials. When mechanically twisted, SMA materials reject heat to their surroundings, and subsequently absorb heat as they return to their originally shape. A thermoelastic cooling system consisting of a SMA plate connected between two rotary actuators could produce usable space cooling by oscillating a SMA core.

Technical Maturity and Recent Developments
DOE funded a thermoelastic cooling project co-researched by UMD, GE, and PNNL through the ARPA-E program. The lead researchers have developed a SMA capable of thermoelastic cooling with the hopes of applying it to HVAC. At the University of Maryland (UMD) Sustainability Workshop in April 2011, UMD professor Ichiro Takeuchi presented on his team's developments with thermoelastic cooling for HVAC applications. The UMD team's proof-of-concept prototypes using thin, nitinol (NiTi) wires as the thermoelastic material showed promising results. The UMD team is currently working with PNNL to design and test a 0.01-ton prototype thermoelastic cooling system (Haas 2012).

Next Steps for Technology
Further development of larger prototypes should reveal the potential of a thermoelastic cooling system for residential HVAC applications. While the thermoelastic process has been proven on a small scale, constructing a reliable prototype unit at sufficient cooling capacity may prove challenging.

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C.10 Turbo-Compressor-Condenser-Expander

Brief Description	This technology combines the compressor, condenser, and expansion device of a typical vapor-compression system into an integrated package for greater heat-transfer efficiency.	
Attribute	**Value**	**Comments**
Systems Impacted	Conventional air conditioners and heat pumps	
Annual Energy Consumption of Baseline Technology	1.74 Quads/yr	All cooling systems, medium replacement potential.
Non-Energy Benefits	Uses natural refrigerants	

Description of Technology

The standard vapor-compression cycle utilizes a compressor, condenser, expansion device, and evaporator to add/remove heat from a space. The turbo-compressor-condenser-expander (TCCE) or isothermal turbocompressor (ITC) integrates these components into a single, motor-driven device.

The TCEE system consists of two sets of radial spokes connected by a thin plenum rotating together by a motor. This integrated process could act as the outdoor unit for a conventional split-system air conditioner or heat pump:

- After leaving the evaporator, refrigerant gas enters the TCCE and is centrifugally compressed outward through the top spokes.
- The refrigerant travels from the upper spokes through the condensing plenum and cools as the spinning spokes generate airflow through the TCCE.
- The rotating bottom spokes collect and expand the cooled refrigerant before exiting the TCCE for use in the evaporator.

The TCCE reduces energy use for vapor-compression equipment by combining systems to maximize heat transfer. The TCCE can operate over a range of liquid-vapor conditions allowing the variable-speed motor to directly control capacity for improved part-load performance.

Technical Maturity and Recent Developments

Appollo Wind Technologies, LLC is developing the TCCE, which was named a "Showcase Technology" at the 2011 ARPA-E Energy Innovation Summit. Their initial proof-of-concept prototype built with off-the-shelf components had a capacity of 1.1+ tons. The company will test additional designs in 2012 using improved components that they believe will increase performance.

Next Steps for Technology

If successfully developed and commercialized, the TCCE would offer a viable CO_2 split-system air conditioner or heat pump for the residential market. Further development of this technology and additional testing for its reliability, safety, and performance will determine its future in residential cooling applications.

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Appendix D Preliminary Analyses

As discussed in Section 2.3, we performed a preliminary analysis of technical energy savings potential and potential next steps toward greater market adoption for each of the 42 technology options we selected after the first round of screening and removal of 10 early-stage technology options. Of these 42 technology options, we performed in-depth analyses for 19 priority technology options (Section 3).

This section includes the preliminary analysis write-ups for the remaining 23 technology options, organized in alphabetical order, as presented in Table D-1.

Table D-1. 23 Technology Options Selected for Preliminary Analysis

Advanced Defrost Methods for Heat Pumps	Magnetic Cooling System
Advanced Evaporative Coolers	Microchannel Heat Exchanger
Airflow-Optimizing System	Mixed-Mode Conditioning
Air-Ground Heat Exchanger	Night Sky Radiant Cooling
Chilled-Beam Radiant Cooling	Nighttime Ventilation Cooling
District Heating and Cooling	Quality Installation
Ductwork in the Conditioned Space	Seasonal Thermal Energy Storage
Evaporative Roof Cooling	Smaller Centrifugal Compressors
Evaporatively Cooled Condensers	Smart Ventilation Systems
Hot-Dry Air Conditioner	Swimming-Pool Heat Sink
Improved Duct Systems	Variable-Stroke Compressor
Liquid-Desiccant Air Conditioner	

D.1 Advanced Defrost Methods for Heat Pumps

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Electric-Resistance Defrosts - Electricity		0.03 Quads/yr	Commercially Available
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Low	Reduced Maintenance	High	Medium

Description of Technology

Advanced defrost methods for heat pumps are controls that regulate the defrost cycles of heat pumps. The technology uses special sensors for monitoring temperatures and ambient conditions to determine appropriate frequency and duration of the defrost cycles. A processor optimizes the defrost cycles based on previous defrost cycle information.

How Technology Saves Energy

The technology regulates the length and frequency of defrost cycles, eliminating unnecessary defrost time.

Replacement Potential

A contractor can add a demand-defrost control system on to an existing heat pump or refrigeration system.

Potential Scope of Impact

Advanced defrost controls replace automatic-timed defrost cycles. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.03 Quads of electricity per year.

Energy Savings Performance

Based on literature search, we estimate demand defrost can save 10% of unit energy consumption.

ADA Technologies (2012) claims it's intelligent defrost controller can save 7-15% of refrigeration-cycle energy consumption.

Cost Information

Industrial Controls Online (2012) estimates a payback period for a demand-defrost system to be approximately one year.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

Reducing the number of defrosts reduces the equipment wear. This can significantly reduce maintenance costs.

Technical Maturity and Recent Developments

This is a commercially available technology.

Barriers to Market Adoption

Heat pumps gain a defrost credit in the DOE test procedure, so a good demand defrost system may not have all the energy savings acknowledged.

Opportunities and Next Steps for Technology

The technology is commercially available in the U.S., but does not have many manufacturers. This technology needs incorporation into DOE test procedures beyond a simple demand defrost credit.

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D.2 Advanced Evaporative Coolers

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Central Air-Conditioning Systems		0.19 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Improved IAQ	Medium	Medium

Description of Technology

For decades, residential buildings in dry regions of the country have incorporated various evaporative cooling strategies to provide energy-efficient space cooling. Typical direct evaporative coolers (also known as "swamp coolers") require consistently low wet-bulb temperatures to operate, limiting the capacity and geographic reach of the system to Mountain states and parts of the Southwest. New technologies such as indirect, indirect/direct, hybrid, and DEVap cooling systems improve the energy efficiency, water consumption, and applicable regions for residential evaporative cooling.

- Unlike direct systems that pass supply air through a wetted surface and increase its humidity, indirect evaporative coolers pass supply air through a heat exchanger channel that is evaporatively cooled by a secondary airstream. Because the supply air never comes in contact with the water, it retains its humidity level, which leads to more comfortable space cooling.
- An indirect/direct evaporative cooler (IDEC) combines both an indirect stage to cool without moisture addition, and a direct stage to provide additional cooling with minimal moisture gain. This multi-stage system is more efficient than an indirect evaporative cooler and allows for independent capacity and humidity control in various conditions.
- Hybrid systems combine an indirect evaporative cooling component with a conventional DX cooling coil to further expand the use of evaporative systems to additional climate zones.
- The DEVap system, developed at NREL, combines both liquid desiccant and evaporative cooling technology, performing both latent cooling and dehumidification in one device. This system consists of a first stage that dries and cools incoming air using a liquid desiccant stream and a second stage that evaporatively cools a water layer using a portion of the dried air, further cooling the supply air.

How Technology Saves Energy

Because the only energy-consuming components in an evaporative cooler are fans and a water pump, without the use of an energy-intensive compressor, its energy consumption is significantly lower than for a conventional DX air-conditioner. The DEVap system requires additional energy from a low-quality heat source (natural gas, solar thermal collectors, or waste-heat sources) to regenerate the liquid desiccant.

Replacement Potential

Traditionally, evaporative coolers needed to be placed on an outdoor pad, or in the attic with their own duct system, but the new advanced systems can integrate with the primary ductwork.

Although easier for new construction, these units could be placed similar to a standard air-handling unit in a garage, basement, or attic to facilitate connections to outdoor air vents. However, if the current air-handling unit resides in an internal utility closet, the added cost and complexity of the inlet and exhaust vents will likely prohibit conversions from DX systems. For this analysis, we classify advanced evaporative coolers with a medium replacement potential.

Potential Scope of Impact
Advanced evaporative cooling technologies displace conventional DX cooling systems and other evaporative cooling technologies. As an example technology, we analyzed DEVap for technical energy savings potential in each climate region, shown in Table D.2-1. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.19 Quads of electricity per year.

Table D.2-1. Technical Energy Savings Potential of a DEVap Unit for Each Climate Region

Climate Region	Technical Energy Savings Potential (Quads/yr)
Hot-Dry / Mixed-Dry	0.10
Marine	0.01
Hot-Humid	n/a*
Mixed-Humid	0.05
Cold / Very Cold	0.03
Total	**0.19**

*Not applicable because DEVap consumes more energy than the baseline DX system in this climate zone.

Energy Savings Performance
Dieckmann et al. (2009) discussed various advanced evaporative cooling technologies and stated that they typically have a unit energy savings of 75% compared to DX cooling systems in applicable regions.

Davis Energy Group (2004) developed and tested an IDEC system that exhibited 90% unit energy savings over DX cooling systems in hot-dry regions.

SWEEP/WCEC (2007) detailed a number of advanced evaporative cooler designs, and stated that hybrid evaporative systems could achieve a 50% reduction in energy consumption compared to standard DX systems.

Kozubal et al. (2011) developed models for the DEVap process and compared it to a high efficiency DX system in various U.S. cities. The modeled DEVap system reduced source energy consumption and peak electricity demand for each climate zone over a DX system with a dehumidifier. Lab testing of initial prototypes has generally verified these models and uncovered additional areas for design improvement (Kozubal et al. 2012). Because most homes do not have a separate dehumidifier, we adjusted NREL's estimates of unit energy savings for DEVap to remove the portion of savings associated omitting a separate dehumidifier (see Table D.2-2).

Table D.2-2. Unit Energy Savings of a DEVap unit for Each Climate Region

Climate Region	Unit Energy Savings Over a DX System (%)*
Hot-Dry / Mixed-Dry	67%
Marine	65%
Hot-Humid	-2%
Mixed-Humid	26%
Cold / Very Cold	29%

*NREL estimates unit energy savings for a DEVap unit compared to a DX system with separate dehumidifier. We adjusted NREL's estimates to remove the portion of savings associated with the dehumidifier because most U.S. homes do not have a separate dehumidifier.

Cost Information
Cooperman et al. (2011) investigated the cost savings of evaporative coolers compared to standard DX equipment for a number of cities in the Southwest. The cities of Albuquerque, Denver, Las Vegas, and Phoenix could save 82-86% on yearly cooling costs, including water consumption charges.

Dieckmann et al. (2009) stated that advanced evaporative coolers cost 2-3 times more than direct evaporative coolers, and have similar costs to DX cooling systems.

PIER (2005) estimated the uninstalled cost for a 3-ton, residential indirect/direct evaporative cooler to be $2500-3000.

Shepherd-Gaw (2011) estimated the payback period for a hybrid evaporative cooler to be 1-5 years depending on site-specific conditions and electricity rates.

Kozubal et al. (2011) projected a preliminary equipment cost for a 3-ton DEVap system to be around $7,500, but noted anticipated design improvements would decrease the unit and heat exchanger size, lowering cost.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains
Because they operate more efficiently than DX equipment during peak conditions, evaporative coolers provide significant peak-demand savings. Most advanced evaporative coolers deliver high amounts of outdoor air (often 100% outdoor air) that improves IAQ.

Technical Maturity and Recent Developments
Indirect, IDEC, and hybrid evaporative coolers are commercially available from several manufacturers in many markets. The DEVap system requires additional development through

short-term R&D activities. NREL recently developed and tested breadboard components of the DEVap. Although NREL anticipates that DEVap will first be introduced for commercial rooftop applications, design advancements might improve the feasibility for residential systems, despite the more challenging installation requirements for residential retrofits.

Barriers to Market Adoption

Although much work has been done to try and expand their applicability, presently, evaporative cooling is only effective in certain dry regions of the U.S. Because unit energy savings decrease outside the traditional evaporative market (e.g., Hot-Dry/Mixed-Dry region), the added installation cost over a DX system extend the payback for replacement applications in Mixed-Humid and Cold regions. Perhaps because of capacity, humidity, and maintenance problems associated with direct evaporative coolers, many HVAC contractors and consumers have not yet embraced recent advances in evaporative technology, even within the Hot-Dry region. Some parts of the country may experience droughts that put a premium on water consumption. A direct evaporative cooler consumes 3 gallons per ton hour, where as the water consumption of advanced evaporative coolers would vary based on the specific technology and application (Cooperman et al. 2011). For example, a DEVap system would consume approximately 1.5 gallons per ton hour (Kozubal et al. 2012).

Opportunities and Next Steps for Technology

Expanding the market penetration and regional availability of evaporative cooling requires additional field testing in a variety of conditions to demonstrate long-term performance of these technologies. Development of a consistent standard to compare the energy efficiency of evaporative coolers to DX cooling systems should help raise consumer awareness. Field tests are needed in areas with hard water to improve maintenance procedures to deal with scale buildup. Continued DEVap prototype refinement and testing is needed to further design improvements to raise efficiency of the liquid desiccant, heat exchanger, and regenerator. Further analysis of the DEVap manufacturing and installation costs is needed to better quantify DEVap’s cost attractiveness, especially for more humid regions of the country.

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D.3 Airflow-Optimizing System

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Air Conditioning and Ventilation		0.04 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Cleaner Air; Reduced Noise	High	Medium

Description of Technology
The airflow-optimizing system is a software product that evenly distributes airflow to reduce stagnant air pockets and drafts. The software system controls the home's ductwork, reducing the airflow speed of air entering the conditioned space and evenly distributing the air in all directions. The airflow-optimizing system balances the temperature of the room, reducing the temperature stratification.

How Technology Saves Energy
Bauer (2012), an airflow-optimizing system creator, claims its airflow-optimizing system reduces the amount of energy necessary by improving mixing of fresh and indoor air. The airflow-optimizing system continuously regulates the airflow in a room and continually mixes the air, reducing air stagnation and improving temperature distribution. This even temperature distribution permits lower thermostat set points for the same comfort level, thereby saving energy.

Replacement Potential
Bauer claims its airflow-optimizing system can be retrofitted onto existing single-duct and dual-duct systems or on a new duct system. The airflow-optimizing system may not be suitable for existing homes with difficult-to-reach ductwork.

Potential Scope of Impact
The airflow-optimizing system would reduce the energy required for heating and cooling, but requires ductwork in the home. The airflow-optimizing system is not limited by climate; Bauer and partners have installed airflow-optimizing systems in Australia, Germany, Austria, and Switzerland. Bauer has only installed systems on commercial buildings; therefore, single-family residential applications are unknown. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.04 Quads of electricity per year.

Energy Savings Performance
We estimate the airflow optimizing system reduces energy consumption 30% based on the following literature:

- An installation at Cologne/Bonn airport showed 37.3% energy savings over one year.

Cost Information
Bauer did not provide cost information, but an installation at Cologne/Bonn airport showed a payback period near one year with 37.3% annual energy savings.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains
The airflow optimizing system would reduce peak-demand proportionally to the energy savings.

Other claimed benefits of BOS include reduced noise (reduced airflow) and improved air quality (no concentrations of pollutants in the breathing air zone).

Technical Maturity and Recent Developments
This technology is commercially available, but availability appears limited in the United States. Bauer has over 1000 installations throughout Europe and Australia, but does not mention of any United States installations.

Barriers to Market Adoption
Literature search did not reveal any barriers to market adoption.

Opportunities and Next Steps for Technology
We recommend studying the airflow-optimizing system for viability in residential applications and validating energy-saving claims.

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D.4 Air-Ground Heat Exchanger

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
All HVAC Systems		0.05 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Ventilation	Low	High

Description of Technology

The air-ground heat exchanger is an underground heat exchanger (piping system) that uses the relatively consistent temperature of the earth to heat or cool air. Ground temperatures only vary a few degrees from annual average temperatures at depths greater than 1.5 meters. This allows for cooling in the summer months and heating in the winter months, particularly in locations with large temperature extremes. The air-ground heat exchanger is unlikely to produce enough heating and/or cooling to completely condition the air, therefore, a supplemental heating/cooling system is required.

Two types of systems exist: open and closed.

- In an open system, air is drawn from the outside, either by natural convection (using a solar chimney), or via a fan or pump. The outside air flows through a filter and passes through tubing (approximately 100 feet for a typical residential installation) before reaching the building.

- In a closed system, either natural convection or a pump/fan draws air from inside the building then circulated multiple times through underground tubes.

Variations of the air-ground heat exchanger exist, such as a combined system (open system when needing fresh air), or a system directing the air into either a central air conditioner or a heat pump.

The air-ground heat exchanger installations depend on a variety of factors, such as soil conditions (soil content, moisture), annual average temperature and humidity. The air-ground heat exchanger typically requires supplemental dehumidification in the pipes because excess humidity can breed molds. Rehau, an international polymer solutions company, developed an air-ground heat exchanger system with an anti-microbial inner pipe layer (Rehau 2012).

How Technology Saves Energy

The technology saves energy by heating/cooling (or pre-heating/pre-cooling) the air using the ground as an energy source. The air-ground heat exchanger system directs air through tubes buried approximately 3 meters deep in the ground to exchange heat.

Replacement Potential

The process of implementing the air-ground heat exchanger requires a custom installation and excavation of the ground. While the air-ground heat exchanger can be retrofit to an existing or new HVAC system, installing the air-ground heat exchanger would be much easier in new construction while ground excavation is already occurring.

Potential Scope of Impact

The air-ground heat exchanger would heat and cool residential and small-commercial buildings. Although the air-ground heat exchanger is better suited for low-humidity areas, with proper dehumidification, the air-ground heat exchanger is useful in many locations in the U.S., although less so in consistently mild states, like Hawaii. A supplemental HVAC system would likely be required particularly in the northern U.S. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.03 Quads of natural gas, and 0.02 Quads of electricity per year.

Energy Savings Performance

Girja Sharan (2002) studied an open configuration, single-pass (the air flows once through the underground pipes) air-ground heat exchanger system in India in 2002. Using a 400W blower, he found an average cooling mode COP of 3.3 and average heating mode COP of 3.8.

Cost Information

An air-ground heat exchanger system includes tubing, dehumidification, excavation costs, and labor. Excavation costs and labor, highly dependent on size, would account for a majority of the costs.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

The air-ground heat exchanger is most effective during peak demand. The more extreme the temperature, the more energy transferred to the air for (pre)heating or (pre)cooling. Based on Sharan's air-ground heat exchanger study in India (Sharan 2002), an air-ground heat exchanger system with a temperature different between air and ground of 28°F could have an instantaneous COP of 5.0 with a 400W blower. In areas where the average annual temperature is around 50°F, like Boston, MA, temperatures can reach 100°F and 0°F.

Open systems also benefit from bringing fresh air into the building.

Technical Maturity and Recent Developments

This is an emerging technology with limited availability in the U.S. market today. Air-ground heat exchanger systems in the U.S. are mainly limited to niche contractors and do-it-yourselfers. Rehau manufactures the Awadukt Thermo® system in England, where air-ground heat exchanger systems and contractors are more common.

Rehau developed the first air-ground heat exchanger system (Awadukt Thermo®) with an anti-microbial inner pipe layer, reducing the concerns of harmful molds and improving air quality.

Barriers to Market Adoption

DOE EERE notes a variety of issues with the air-ground heat exchanger technology

(EnergySavers 2012). The air-ground heat exchangers can be breeding ground for mold, fungi, and bacteria, and air quality may curb consumer enthusiasm about the systems. Open air-ground heat exchangers are susceptible to insects and small animals. Air-ground heat exchangers perform poorly in hot and humid areas because the ground does not remain cool enough and supplemental dehumidification is necessary. DOE notes the technology is prohibitively expensive, but does not quantify the amount.

Opportunities and Next Steps for Technology

We recommend analyzing the air-ground heat exchanger for viability in dry areas with high seasonal variance in temperatures.

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D.5 Chilled-Beam Radiant Cooling

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Cooling and Ventilation Systems		0.03 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Medium	IAQ/Comfort	Low	High

Description of Technology

Chilled-beam radiant cooling uses chilled water in modular ceiling systems for space cooling. Chilled water flows into specialized ceiling panels that use convection and radiative heat transfer to cool a room. Two types of chilled-beam systems include:

- Passive chilled beam consists of only piping and fins, chilling the air and using convection to circulate it.
- Active systems use supplemental ventilation air to distribute the cooling away from the panel. The air passes through nozzles to create additional airflow, forcing convention, allowing for twice the cooling density over passive systems (and standard convection).

Description of How Technology Saves Energy

Chilled-beam systems do not require air delivery to condition spaces; therefore, eliminating the need for a fan. Chilled water also has a higher heat capacity than air so pumping energy is significantly less than the equivalent energy for air movement.

Replacement Potential

Literature search did not find information regarding replacement potential for residential applications of chilled-beam systems.

Potential Scope of Impact

Chilled-beam systems are suitable for most climates in the U.S., but are not recommended for climates with high humidity. Chilled beam would likely require supplemental cooling to reach full cooling capacity in residential applications. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.03 Quads of electricity per year.

Energy Savings Performance

We estimate 20% cooling load savings for commercial applications based on the following literature:

Sachs, et al. (2009) estimate that a radiant heating/cooling system would reduce energy consumption by approximately 20% compared to a standard VAV system.

Roth, et al. (2002) estimates 15-20% savings in space cooling, and 20-30% savings on ventilation.

We estimate residential applications to save a similar amount.

Cost Information

Literature search did not provide cost information for residential applications of chilled beam, however, based on the following literature, chilled-beam costs would be similar to a VAV HVAC system.

Sachs, et al. (2009) estimates installing chilled beam saves 5% compared to a typical VAV HVAC system installation.

Peak-demand Reduction and other Benefits Beyond Energy Efficiency Gains

Peak demand would be reduce proportionally to energy savings.

Technical Maturity and Recent Developments

Chilled beam is emerging for residential applications, and has very limited, if any, market penetration in the U.S.

Barriers to Market Adoption

Chilled-beam systems have a higher first cost than typical residential cooling systems. Condensation on the chilled beam is an issue, and although this can be mitigated with dehumidification, this adds additional costs to the system. Chilled beam likely requires supplemental cooling and will require supplemental heating, thus adding an additional cost to the consumer.

Opportunities and Next Steps for Technology

We recommend further study into chilled-beam for residential applicability.

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D.6 District Heating and Cooling

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Central HVAC Systems		0.06 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Reduced Emissions	Low	High

Description of Technology

District heating and cooling (DHC) is a community-based system using a centralized location for generating heat or chilled water for heating/cooling purposes.

For heating, a central plant heats water or generates steam and distributes it via pipes to all the consumers on the network. For cooling, a plant may use cold seawater or lake water from a depth of 250 feet or more or chillers to provide chilled water. Some plants incorporate energy storage as well.

District heating and cooling can vary widely in size, from only a few residential homes to over 100,000 buildings.

How Technology Saves Energy

DHC saves energy by a) using more efficient, larger energy producers, b) using combined heat and power, or c) using renewable resources.

Replacement Potential

DHC is challenging to retrofit, requiring disruptive and expensive installation of piping networks and connections to residences and other buildings. Because DHC is a community-based system, multiple residences need retrofitting.

More likely, a community will decide to use district heating and/or cooling prior to home development. Construction of the homes would include infrastructure for DHC connecting residences to the heating or cooling source. Drake Landing Solar Community in Okotoks, Alberta, Canada is an example of a community built around DHC.

Potential Scope of Impact

DHC could provide heating and cooling in most climates in the United States. In areas near a large lake or the ocean, a community of homes could use the cold water to reduce cooling loads. DHC is not suited for rural applications because of the long piping runs required. In DHC with renewable sources, backup fossil fuels may need to supplement heating or cooling. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.03 Quads of natural gas per year, and 0.03 Quads of electricity per year.

Energy Savings Performance

The Drake Landing Solar Community claims 90% of heating needs from renewable (solar) sources. A 2008-2009 Drake Landing Solar Community annual report states 60.4% of heating from the solar DHC.

Cost Information

Kevin Rafferty (1996) estimates the cost of a 256 home system between $920,000 and $1,600,000 in 1996 dollars. In 2011 dollars (adjusting for 2.4% average annual inflation), the current cost of a 256 home system is estimated between $1.3 and $2.3 million.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

DHC could significantly reduce peak demand by utilizing the efficiency of larger and more direct heat/cooling sources. Seawater or lake-source cooling would reduce cooling energy consumption by replacing electricity with cooling from cold water. Using renewable energy as a heat source for DHC reduces fossil energy consumption, reducing peak-demand fossil generation. Combined heat and power reduces peak demand for larger plants and natural gas systems because of improved efficiency producing heat and electricity.

Using DHC can reduce greenhouse gas emissions when using renewable energy or cogeneration.

Technical Maturity and Recent Developments

DHC has been around for over 100 years, although popularity for DHC dwindled in the 1920s and 1950s because of larger power plants for electricity and cheaper fuel options, respectively. (Miller 1985). DHC regained popularity in Europe due to the oil crisis in the 1970s, and it remains a major heating and cooling method for many European countries, such as Iceland, Denmark, Poland, and Sweden.

In the US, larger district heating applications still exist in major cities, such as New York, San Francisco, and New York City, however few smaller residential applications exist. As fuel prices rise, the economics for smaller, community-based DHC improve. With more awareness on the environment, more countries and entities have undertaken renewable DHC projects, such as the Drake Landing Solar Community.

Barriers to Market Adoption

Costs may prevent DHC from becoming widely accepted. DHC may not provide the proper economics for businesses to install and maintain DHC infrastructure, and consumers may not want to pay the additional costs. Additionally, most U.S. infrastructure is not designed for easy DHC retrofit. Building DHC with new communities would alleviate retrofit issues, but over saturation of the housing market (with too many new communities) may slow adoption.

Opportunities and Next Steps for Technology

We recommend studying potential operating and maintenance cost reductions for DHC systems.

DHC would benefit from additional pilots in residential applications and renewable designs. A continued focus on environmental issues will also help DHC.

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D.7 Ductwork in the Conditioned Space

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
All HVAC systems		0.06 Quads/yr	Commercially Available
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Medium	Improved IAQ	Low	Low

Description of Technology

Ducts often run through unconditioned spaces in homes such as attics, garages, crawlspaces, and basements. Installing ductwork in unconditioned spaces can be more convenient for the builder and less costly to install. However, according to the DOE Building America (DOE 2004), poor duct systems in unconditioned space can have 25 to 40% energy losses either by air leakage or heat conduction. Alternatively, ducts can be placed in conditioned space—within the insulated thermal barrier and pressure boundary of the house. Placing ducts in conditioned spaces largely eliminates the energy loss associated with leakage and/or thermal exchanges with ducts because the leakage and/or heat loss/gain provides useful space conditioning.

Description of How Technology Saves Energy

Ducts can lose conditioned air via a) conduction and convection, or b) air leakage. When ducts are located in the conditioned space, these energy exchanges provide useful space conditioning instead of being lost to the outside environment.

Replacement Potential

Installing ductwork in the conditioned space is typically impractical as a retrofit application because ductwork can be hard to reach and expensive to renovate. We do not include finishing a basement or attic because that adds conditioned space, thus increasing energy consumption.

Potential Scope of Impact

Ductwork in the conditioned space would benefit homes in all climates in the U.S. New constructions would be the only suitable option for this technology. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.03 Quads of natural gas per year, and 0.03 Quads of electricity per year.

Energy Savings Performance

We identified several energy savings estimates through a literature review:

- The Partnership for American Technology in Housing (PATH) (2012) estimates savings on heating and air conditioning can be 25% or more.

- In the PATH Tech Specs (2012), the PATH Field Evaluation in Alabama estimated 8% heating and cooling savings from moving ductwork into conditioned space.

- Michael Lubliner (2008), for ACEEE, notes the DOE Building America Project modeled 31% cooling and 39% heating savings in a Washington State Habitat for Humanity home with ducts in conditioned space.

- A California Energy Commission study (2003) estimates the annual cooling savings for a California home with 22% system airflow loss is 5-18% (depending on climate zone and size).

Based on the above, we estimated a 15% national-average unit energy savings for ducts in conditioned space. This is based on a weighted average of nearly 30% energy savings in extreme climates and 10% in moderate climates, with populations in moderate climates about three times those of extreme climates.

Cost Information

A California Energy Commission study (2003) estimates the incremental cost to install ducts in conditioned space is $700, with costs ranging from $0 to $4,000.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

Ductwork in the conditioned space will reduce peak demand in proportion to the energy efficiency improvement.

By placing ductwork in the conditioned space, leaky ducts cannot allow pollutants to seep into conditioned space.

Technical Maturity and Recent Developments

This is a commercial available technology and is used in the United States.

Barriers to Market Adoption

Literature search did not provide any barriers to market adoption for new construction.

Opportunities and Next Steps for Technology

Ductwork in the conditioned space may provide a benefit in new constructions. Building codes could require buildings place ductwork in the conditioned space.

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D.8 Evaporative Roof Cooling

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Cooling		0.25 Quads/yr	Commercially Available
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Reduced Roof Maintenance	High	Medium

Description of Technology

During summer months, the sun can heat roofs to temperatures upward of 160°F in Texas and other southern states (Abernethy, 1985). An evaporative-roof-cooling system sprays water onto the roof surface, which lowers the roof temperature as the water evaporates. Typically, a system includes a series of pipes installed on the roof that have misting nozzles attached to spray water evenly onto the surface of the roof. Programmable controls turn the misting system on and off depending on roof temperature. For example, some systems in Texas begin misting when the roof reaches above 90°F. The system will mist for 10-30 seconds and 'rest' for 3-8 minutes, spraying a thin film of water, just enough to evaporate completely before another cycle (Abernethy, 1985). Any additional water runs off through gutters; anecdotal evidence on Build It Solar, a site promoting green technologies, suggests that just under than half the water sprayed provides useful cooling by evaporating from the roof.

How Technology Saves Energy

As the sun heats a roof during the day, the absorbed heat transfers to, and heats, the interior of the home. Cooling a roof reduces the amount of heat gain into a home, reducing the interior cooling load. Evaporating water absorbs heat at approximately 8700 Btu/gallon. Therefore, 300 gallons of water can cool the average United States home each day, based on a report by Dick Abernethy, president of FAN-JET Evaporative Roof Cooling Systems, in 1985; however, the evaporative roof cooling system would need supplemental space cooling for high demand.

Replacement Potential

Evaporative roof cooling could be installed on many residences using the current roof setup for installation, but would require a supplemental cooling system. The system requires a supply of clean fresh or recycled water.

Potential Scope of Impact

Evaporative roof cooling would work with many homes in the United States, although would be most useful in the southern states. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.25 Quads of electricity per year.

Energy Savings Performance

Japanese researchers (Narumi et al., 2009) tested a roof cooling system on an apartment building with a flat black roof in Osaka, Japan and found energy savings of 22% of the cooling load.

Cost Information

Dick Abernethy (1985) estimated a system for a 103,000 square foot commercial building to cost $36,000 in $1985 ($75,700 adjusted for $2011 using historical inflation data).

Ryesa (2007) for Build It Solar, a website promoting green energy, found the cost of parts to be approximately $150 for a do-it-yourself system in Nebraska. The size of the installation is unclear.

An average U.S. (2,700 square foot) home consumes an average of 400 gallons of water per day. Evaporative roof cooling would increase water consumption by 300 gallons/day, or 75%. Based on $3.00 per 1000 gallons of water, this increased water costs by approximately $30/month.

Literature review provided no additional information regarding residential evaporative roof cooling costs.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

Literature review did not provide information on peak-demand reduction.

Other benefits of evaporative roof cooling include reduced roof maintenance and improved working conditions. Dick Abernethy (Abernethy, 1985) states that cooling a roof reduces thermal shock, thermal expansions of the roof, and roof blistering.

Technical Maturity and Recent Developments

Evaporative cooling has been used in the United States since the 1930s (Abernethy, 1985). Evaporative roof cooling was commonplace until air conditioners took over the market, especially in the industrial and commercial sectors. A few companies, including Patterson and AutoSoft Systems, make evaporative roof cooling systems.

Barriers to Market Adoption

Concerns about water leaking into the home and high water consumption (a 75% increase) may cause residences to question evaporative roof cooling. Economies of scale for evaporative roof cooling currently favor large commercial applications; few manufacturers cater to residential consumers.

Opportunities and Next Steps for Technology

We recommend verifying the energy savings potential of evaporative roof cooling systems for single-family residential applications.

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D.9 Evaporatively Cooled Condensers

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Air-cooled condensers for DX cooling systems		0.03 Quads /yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Equipment longevity	Medium	Medium

Description of Technology

Most direct-expansion (DX) cooling equipment for residential systems utilizes air-cooled condensers. These heat exchangers cool and condense the hot, high-pressure refrigerant gases leaving the compressor. The condenser fan induces outdoor air to flow across the condenser coil to remove heat from the refrigerant through convection. Evaporatively cooled condensers spray water on the condenser to sensibly cool the coil and remove additional heat as the water evaporates off the coils. Water circulates from a sump through spray nozzles onto the coils, evaporates, and exhausts from the condenser fan. The sump is routinely flushed to prevent the buildup of minerals and other debris and maintain proper water conditions.

How Technology Saves Energy

This process, also known as evaporative condenser pre-cooling, lowers the air temperature entering the condenser by 30-40 ˚F reducing the temperature and pressure requirements of the compressor, thereby reducing energy use. Evaporative cooling technology performs best when outdoor temperatures reach their peak, and standard air-cooled condensers lose capacity and performance. The efficiency improvements from evaporatively cooled condensers outweigh the added energy consumption associated with the water pump.

Replacement Potential

Although this technology can be retrofit directly to existing condensing units for larger applications, evaporative features will be incorporated primarily into replacement residential systems.

Potential Scope of Impact

Commonly seen in cooling towers for commercial and industrial buildings, evaporatively cooled condensers would be applicable for most residential applications. This concept already exists for residential room air conditioners that typically use a slinger ring to spray the condenser coils with condensate water from the evaporator. Although this system performs better in hot-dry conditions, it still has an effect across the entire U.S. for cooling. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.03 Quads of electricity per year.

Energy Savings Performance

Verma et al. (2006) simulated the system energy savings of evaporatively cooled condensers in various California climates and determined a 20-40% reduction in cooling energy for single-family residential systems. Greater savings were achieved in hot-dry regions with lower wet bulb temperatures.

McQuay (2004) markets their packaged equipment featuring evaporatively cooled condensers and claims a 27-40% unit energy savings for various U.S. climates.

Davis Energy Group (2008) tested an system using an evaporatively cooled condenser and found an energy savings of 21-33% relative to a 13 SEER system.

Keesee and Bisbee (2010) presented the results of a 30-unit field study for Beutler Corporation's AquaChill evaporative condenser. For a typical single family home in California, the units saved an average of 29%.

Cost Information

Residential systems using this technology have been priced comparably to other high-efficiency (18 SEER) residential units. Because this technology maintains cooling capacity at higher temperatures better than conventional systems, equipment using evaporatively cooled condensers can be downsized by ½ ton (Davis Energy Group 1998).

Davis Energy Group (2008) estimates a $1000/ton incremental cost above a 13 SEER unit.

Keesee and Bisbee (2010) stated that the AquaChill units cost around $650 per ton higher than standard efficiency units.

Water consumption for this technology can be significant as systems can consume 1-3 gal/hr/ton. Additional water treatment may be necessary to maintain performance, depending on local conditions.

Peak-demand Reduction and other Benefits Beyond Energy Efficiency Gains

Because this technology works most efficiently when outdoor temperatures are highest, electrical demand significantly reduces during peak hours, especially for lower wet-bulb temperatures. Keesee and Bisbee (2010) found a peak-demand reduction of over 1kW for a 4-ton residential unit. By reducing the compressor requirements, especially during peak hours, evaporatively cooled condensers may extend compressor lifetimes.

Technical Maturity and Recent Developments

This is an emerging technology with limited availability in the U.S. market today for single-family residential systems. Most research has focused on the potential of this technology for California and Southwest states. Numerous manufacturers offer larger packaged equipment utilizing this technology including Aaon and McQuay. Freus and ThermalFlow have manufactured and sold evaporatively cooled condensers for single-family residential applications throughout the West.

Barriers to Market Adoption

Like many other evaporative cooling strategies, customer concerns of maintenance and longevity are major barriers. Because of the sprayed water, the condenser can become corroded or fouled if proper water treatment and flushing is not maintained. Current practices mitigate customer concerns of Legionella growth by maintaining low sump temperatures, regular sump purging, and yearly disinfecting. Many residential technicians are currently unfamiliar with water treatment strategies and proper application. Increased water use is a serious issue in drought-sensitive areas, particularly during peak summer demand.

Opportunities and Next Steps for Technology

Further modeling and field testing is needed to develop better energy savings estimates and long-term reliability in various regions. Improving on current designs to improve water efficiency and water treatment can reduce both the operating cost and environmental impact of evaporatively cooled condensers. This technology can have a significant impact on peak demand in hot-dry regions and should be supported by utility incentive programs.

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D.10 Hot-Dry Air Conditioners

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
DX A/C systems in hot-dry climates		0.03 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Improved capacity control	Medium	Low

Description of Technology

A hot-dry air conditioner (HDAC) operates using a vapor-compressor system similar to that used in a conventional air-conditioning system. However, conventional systems are rated using humid test conditions, and so manufacturers tend to optimize their performance for humid climates. HDAC designs are optimized for hot-dry climates by tweaking standard components found in conventional air conditioners (Buntine et al., 2008). Adjustments may include:

- Controls to minimize latent capacity under dry indoor conditions through higher-saturation-temperature and airflow across the evaporator coil;
- Controls to increase latent capacity when indoor moisture rises significantly; and
- Increased condensate retention on the evaporator coil along with controls to evaporate moisture off the coil after compressor shut-down for additional cooling.

How Technology Saves Energy

Currently, the energy conservation standards for air-conditioners are based on an artificially calculated “average” cooling-season weather conditions across the United States. Because of this, commercially available air conditioners today are not designed to perform optimally in hot-dry conditions that are prevalent in southwestern states, including California, Arizona, New Mexico, Colorado, Utah, Nevada and parts of western Texas. By increasing sensible capacity (high sensible heat ratio) through modifications to heat exchangers and airflow patterns, and by using variable-speed motors, HDACs can maintain desirable indoor conditions with decreased energy consumption.

Replacement Potential

Any residential HVAC system installed in a hot-dry climate, including California, Mountain states and parts of Texas, would benefit from this technology option. This technology would be implemented through replacements of existing unitary systems, and component retrofit in certain situations.

Potential Scope of Impact

New and existing residential buildings with DX air-conditioning systems in hot-dry climates. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.03 Quads of electricity per year.

Energy Savings Performance

According to Buntine, et al (2008), the results from laboratory and field testing demonstrated energy savings of up to 20%.

Proctor Engineering Group (2007) conducted field testing on numerous prototypes throughout California that realized energy savings of 17% to 29%.

Cost Information

Buntine, et al. (2008) estimates the incremental cost of HDAC at $246 for a 3-ton and $67 for a 5-ton unit in California. These estimated were derived using the DOE methodology as used in federal rule setting. The results are similar to a previous study produced by LBNL for the CEC (Rosenfeld et al., 2005).

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

According to Buntine, et al. (2008), the results from laboratory and field testing demonstrated peak-demand reductions of up to 35%. Regions with hot-dry climate tend to be summer peaking utility regions, and air conditioning is the primary cause of the peaks. In California, residential air conditioning has a ratio of peak load to average load of 3.5 to 1. HDACs also provide increased capacity control over conventional systems.

Technical Maturity and Recent Developments

This is an emerging technology with limited availability in the U.S. market today. Buntine, et al., (2008) developed several prototypes with various manufacturers as part of the PIER project for laboratory and field testing. Downey (2009) discusses strategies to increase system efficiency in hot-dry climates using retrofit components such as variable-speed blower motors and improved controls. Using a more efficient blower motor to increase evaporator airflow raises the sensible heat ratio and tuning blower controls to operate after compressor shutoff adds cooling capacity by evaporating condensate on the indoor coil.

In October, 2011, regional energy conservation standards for central air conditioners became effective in the U.S. By creating three regions (North, Southeast, and Southwest), DOE and other industry groups hope to encourage manufacturers to design equipment that maximizes efficiency in those specific climate zones. The minimum SEER rating for the Southwest region, which includes hot/dry climate zones, increases from 13 to 14, with additional EER requirements based on capacity.[11] With a compliance date of January 1st, 2015, this improved Southwest regional standard should boost the development of HDACs.

Barriers to Market Adoption

The market would be able to adopt HDAC once it is commercially developed. However, the energy cost savings must be sufficiently large to justify the incremental cost of HDAC, which is not yet demonstrated outside of California. While Buntine, et al. (2008) suggests that the industry stakeholders engaged during the study "indicated confidence and a willingness to sell

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[11] For units with a rated cooling capacity less than 45,000 Btu/h, minimum EER = 12.2. For units with a red cooling capacity equal to or greater than 45,000 Btu/h, minimum EER = 11.7.

and install HDAC units" in California, similar level of enthusiasm would be required in other applicable states to be able to capture significant portions of the addressable market.

Opportunities and Next Steps for Technology

This technology is intended for application in southwestern United States. While the performance potential of HDAC is well documented for applications in California, additional demonstrations may be needed in other hot-dry areas with more extreme weather conditions (e.g., Arizona and New Mexico).

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D.11 Improved Duct Systems

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
All HVAC Systems		0.05 Quads/yr	Commercially Avail.
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Retrofit**	**Cost/ Complexity**
Medium	Improved Comfort	High	Medium

Description of Technology

Many issues can arise during and after an installation of a duct system, most of which reduce the efficiency of a duct system. Table D.11-1 lists various improvements to the duct system would relieve issues and enhance efficiency.

Table D.11-1. Various Improvements to Common Duct Issues (Hamilton, Roth, and Brodrick 2003)

Issue	Improvement
Disconnected Ducts	Eliminate disconnected ducts by ensuring ducts line up at installation (or during a repair). Ensure proper support for the ducts and connections and correctly apply mastic to connections. (Hamilton, Roth, and Brodrick 2003).
Cracked Ducts	Aerosol duct sealing can significantly reduce leakage in duct systems. A contactor disconnects the duct system and blows an aerosol spray through. The aerosol adhesive flows through the holes and cracks, sealing them.
Inadequate Insulation	Innovative methods of insulation improve energy efficiency for new and existing ductwork. Duct boards provide a high-R-value (4.3 – 8.7) alternative to metal ductwork and duct liners provide protection against heat gain/loss as insulation for sheet-metal and/or flexible ducts.
Poor Design and Poor Airflow	Poor design includes over/undersized ducts, improper airflow, pressure drops, and poor duct layout. Proper design includes installing the correct size of ducts for the HVAC system, reducing pressure drop and maintaining airflow. Properly stretching flexible ducts eliminates unnecessary friction and turbulence. Additionally, removing abrupt transitions and bends and properly sizing inlet and outlet ducts will improve airflow, lowering air-moving energy consumption by up to 30%.

How Technology Saves Energy

Reducing air leakage in residential systems reduces energy losses in conditioned air. Duct design, and duct airflow will reduce losses caused by conduction, turbulent flow, and moving air by fan. Improved insulation reduces thermal losses in unconditioned space.

Replacement Potential

The potential to improve duct systems varies from system to system, and most improvements highly dependent upon duct system accessibility. More accessible existing systems are easier to improve; however, literature search did not provide estimates of accessible duct systems in the United States. Most systems could use an aerosol duct sealing to repair cracked ducts. Redesigning an existing duct system is generally impractical.

Potential Scope of Impact

Typical duct systems in the U.S. have some form of duct issue, whether air leakage or poor insulation (NREL 2004). Over 90% of U.S. homes use duct systems, the impact of improving more accessible systems could be significant. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.02 Quads of natural gas per year, and 0.03 Quads of electricity per year.

Energy Savings Performance

LBNL researchers (Jump, Walker and Modera 1996) estimate an average of 18% HVAC energy savings for duct system improvements. Savings depend highly on the system, as savings varied from 5-57% of HVAC energy savings in the study.

Cost Information

System improvements vary in cost. Toolbase.org estimates aerosol duct sealing to cost $300-$1800 for a single-family home. Adding insulation and sealing gaps with butyl tape and mastic costs $500 - $1500 ($2011 using historical inflation data) (LBNL, 1996). Literature search did not provide additional cost information for other improvements.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

Improved duct systems lower the incremental summer peak demand of a residence in proportion to the energy saved.

Improved ductwork will also provide improved comfort by reducing infiltration of humid or polluted air.

Technical Maturity and Recent Developments

Improvements to duct systems are commercially available in the United States. However, due to barriers to market adoption (in the following section), only a limited amount of residential consumers improve their systems.

Barriers to Market Adoption

Consumers may not improve ductwork because they do not visibly see any issues, thus may hesitate to invest money. Lack of education about duct systems contributes to duct issues going undiagnosed.

Opportunities and Next Steps for Technology

Improving education about duct systems may increase the adoption of duct improvements. Increasing maintenance checks on duct systems or reducing costs of duct improvements would cause more consumers to opt for duct improvements. Improved building codes requiring new homes to properly install duct systems (with sealed ducts) would eliminate the issues early.

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D.12 Liquid-Desiccant Air Conditioner

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
DX cooling systems in humid environments		0.03 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Medium	Improved IAQ, comfort	Medium	High

Description of Technology

Outdoor air contains both sensible heat (temperature) and latent heat (the energy required to condense or evaporate water); both of which must be removed to provide suitable indoor conditions. A typical DX cooling system decreases the coil surface below the dew point, condensing the water vapor which removes latent heat from the air. Desiccants are materials that have a high affinity to water vapor, and can remove water from moist air when exposed to an airstream. A liquid-desiccant air conditioner (LDAC) uses a liquid desiccant to absorb moisture from supply air to both dry and cool the incoming air. When the desiccant removes water vapor from the air, the latent heat content of the air decreases and becomes cool.

After capturing moisture, the liquid desiccant is regenerated by a heating source to release the water vapor back to ambient. By regenerating the solution, the liquid desiccant can remove additional moisture, continuing the cooling process   Common liquid desiccants include glycols, halide salt solutions, lithium bromide, lithium chloride and other salt solutions. LDACs have two main components (Dieckmann 2008):

- A conditioner that exposes strong concentrations of liquid desiccant to the supply air, absorbs water vapor from the supply airstream, and feeds weakened concentrations of liquid desiccant to the regenerator.
- A regenerator that heats the desiccant, releasing water vapor to the exhaust airstream, and returns the liquid desiccant back to the conditioner at strong concentrations.

LDACs heat the liquid desiccant solution in the regenerator using natural gas, a heat pump, or low-grade heating sources such as waste, process heat, or solar-heated water.

How Technology Saves Energy

LDACs can offer large energy savings in humid environments, especially when used in dedicated outdoor air systems (DOAS). Typical vapor-compression systems must deal with latent loads by overcooling the air to remove humidity and then reheating it to reach optimum interior temperatures. The LDAC significantly reduces the latent load experienced by a cooling system while consuming a fraction of the energy required by traditional systems. When used with a free source of heating, LDACs can achieve even higher efficiencies.

Replacement Potential

Although the cooling capacities and size of current systems restricts LDACs to multi-family residences, this technology could be expanded for most cooling applications. Existing buildings with air-based delivery systems could incorporate LDAC units.

Potential Scope of Impact

Because LDAC units reduce latent cooling loads without impacting sensible loads, they are most effective in climates with moderate to high humidity levels. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.03 Quads of electricity per year.

Energy Savings Performance

Sachs et al. (2009) states that, in hot-humid climates with large latent loads, LDACs could reduce HVAC costs 30% by replacing the strategy of over-cooling and reheating air. Compared to a commercial rooftop unit (12 EER), a LDAC would save 66% on cooling electricity consumption.

Dieckmann et al. (2008) notes that a high-efficiency LDAC system (COP = 1.2) used as part of a larger HVAC system (as a DOAS) could achieve primary unit energy savings of 15% compared to conventional systems using the over-cooling and reheating strategy, but negligible for heat pipes. Building users can increase the efficiency of LDACs by using solar-heated water streams or waste-heat streams to regenerate the desiccant. By using these strategies, building users could obtain primary unit energy savings of 20-25%.

Cost Information

Dieckmann et al. (2008) noted that once developed, a LDAC would have a cost premium of 65% compared to a comparable vapor-compression system with a DOAS.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

By using a heating source to drive cooling instead of a mechanical compressor, LDACs can achieve significant peak-demand savings. Because they provide humidity control independently of sensible cooling, LDACs may improve IAQ by introducing additional outdoor air.

Technical Maturity and Recent Developments

A basic LDAC (using a single-effect regenerator) is a commercially available technology, but with low market penetration. However, a more advanced LDAC (one that uses higher-effect regenerators) is not commercially available, and requires short-term R&D activities. The efficiency of the regenerator limits the efficiency of the overall system. Further development may involve double-effect regeneration, triple-effect regeneration, or solar-thermal heating for regeneration.

Barriers to Market Adoption

Lowenstein et al. (2008) noted that use of volatile or corrosive liquid desiccants would pose a barrier in terms of convincing users to adopt the technology. For development of solar-assisted LDAC systems, many sources noted that the high cost of evacuated-tube collectors is a significant barrier to their adoption.

Opportunities and Next Steps for Technology

Lowenstein et al. (2008) noted the following research needs for LDAC, which will accelerate the development and adoption of LDAC units:

- Identification of a noncorrosive desiccant
- Development of an air-cooled unit to replace units using cooling towers
- Improvement of the wetting and rewetting of the contact surfaces of the LDAC
- Improvement of the COPs of current regenerators
- Application of advanced evaporative-cooling techniques to LDACs
- Development of active management systems for managing desiccant quality and chemistry.

In addition, additional field testing is needed to provide more reliability and safety data for these units. Advancing solar-assisted units will require investigation of cost-reduction measures and designs that can reduce the cost of solar-thermal water heating.

Potential Combination with DEVap Technology

Liquid desiccant systems can be enhanced through the use of advanced evaporative cooling techniques. One technology that integrates these technologies is a DEVap A/C, which pairs a liquid desiccant air conditioner with an indirect evaporative cooling unit. This combination overcomes the limitations of both systems; a LDAC can provide dehumidification in hot and moist incoming air, while an indirect evaporative cooling unit can provide cooling (through humidification) in hot and dry incoming air. The DEVap system represents a complete cooling and dehumidifying system that can operate in both moist and dry conditions (Kozubal, et al. 2011). Current DEVap designs pursued by NREL may also offer improved containment of the liquid desiccant through the use of an innovative vapor-permeable membrane.

Thus, a fully developed DEVap system may enhance the performance and safety offered by a conventional LDAC system. See Section D.2 for more information about DEVap A/C systems.

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D.13 Magnetic Cooling System

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
DX cooling and heat pump systems		0.35 Quads/yr	R&D
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Medium	Eliminates refrigerant use	Medium	High

Description of Technology

Magnetic cooling is based on the magnetocaloric effect, a phenomenon in which a paramagnetic material exhibits reversible temperature change when exposed to a changing magnetic field in the following process:

- An applied magnetic field aligns randomly oriented electron spins in the paramagnetic material, raising the material's temperature
- This heat is rejected from the material to its surroundings
- Upon removal of the magnetic field, the electron spins of the magnetic material return to their randomized state and cools the material
- The material then absorbs heat from the space to be cooled and the cycle then starts again.

The temperature gradient and subsequent capacity of magnetic cooling systems varies with the strength of the applied magnetic field. Dieckmann, et al. (2007) reports that permanent magnets suitable for air-conditioning applications can only produce a magnetic-field strength of up to 2 Teslas (T).[12] The investigators state that, because the maximum temperature change achievable by a 2 T magnetic field is 5 °C, some type of regenerative cycle is necessary for magnetic cooling cycle to be viable for space cooling in residential buildings.

How Technology Saves Energy

The magnetic cooling cycle applies a cooling approach that is fundamentally different from the conventional vapor-compression cycle. The current aim of ongoing R&D is to improve the energy performance of the magnetic cooling system to exceed that of the vapor-compression system.

Replacement Potential

The technology does not require any changes to the way the cooled air is delivered to conditioned spaces; however, it does require total replacement of the cooling plant, which would require some additional effort if implemented as a retrofit solution. Otherwise, the technology would be applicable for most residential buildings.

[12] The investigators report that, while stronger magnetic field could induce greater temperature change (e.g., magnetic field strength of 10 T could provide temperature drop of approximately 25 °C), obtaining magnetic fields of such strength would require significant parasitic energy consumption to power superconducting electromagnets. Powering such magnets would defeat the purpose of introducing magnetic cooling to replace the vapor-compression cycle.

Potential Scope of Impact

If successfully developed, the magnetic cooling cycle could replace vapor-compression cooling systems for most residential applications. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.35 Quads of electricity per year.

Energy Savings Performance

Since the technology is still in an early R&D stage, the energy savings performance of the magnetic cooling cycle for residential HVAC applications is not yet known.

According to Gschneidner, et al. (2008), the magnetic refrigeration system has the potential to reduce energy consumption by 20% over a conventional vapor-compression system.

Boeder, et al. (2006) finds through a computer simulation that a 23 SEER magnetic AC system is 28% more efficient when compared to an 18-SEER conventional vapor-compression system. This implies an overall efficiency improvement of nearly 50% compared to a baseline 11.2-EER unit.

Cost Information

Magnetic cooling technology is too early in development to project equipment costs. However, Dieckmann, et al. (2007) and other publications note that the permanent magnets used to induce magnetocaloric effect accounts for a significant portion of the cost of the prototype systems developed so far. Worldwide demand for permanent magnets has increased in recent years and is projected to continue the trend into the future. It is unknown what affect this would have on the costs for a magnetic cooling system.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

If applied to residential air-conditioning systems, magnetic cooling cycle could provide modest reduction to peak demand through reduced energy consumption. Also, because the magnetic air-conditioning system relies on magnetocaloric effect to pump heat, it eliminates the use of chemical refrigerants that can have global climate impacts.

Technical Maturity and Recent Developments

Equipment using the magnetic cooling cycle is not commercially available. There are significant technical issues that will require long-term R&D efforts to resolve. According to research publications including Phan, et al. (2007), Dieckmann, et. al. (2007), Liu, et. al. (2009), and Gshneidner et al. (2008), current research efforts have focused on either: a) improving the cooling capacity of prototype systems using current magnetocaloric materials and permanent magnets; or b) identifying or developing new permanent magnets and magnetocaloric materials. Most of these efforts focus on near-room-temperature refrigeration applications.

A number of leading scientists and engineers from around the world have formed a working group on magnetic refrigeration in the IIR (International Institute for Refrigeration) to promote magnetic cooling as a viable, energy-efficient and environmentally friendly cooling technology. Leading RD&D entities include the Center for Neutron Research (Liu, et al. 2009) at the National Institute of Standards and Technology (NIST), University of Maryland and Iowa State

University. Astronautics Corporation of America is another major player in the RD&D of magnetic air-conditioning system, and has designed, constructed and tested a subscale engineering prototype of a magnetic air-conditioning system in collaboration with Ames National Laboratory (Boeder, et al. 2006).

Barriers to Market Adoption

A potentially significant barrier to the market adoption of magnetic-cooling technology is the volatile nature of the global market for rare-earth metals. Gschneider, et al. (2008) notes that the cost of neodymium, a part of neodymium permanent magnet that will likely be used for residential applications, rose by a factor of 3.5 through a two-year period beginning in January 2005. This trend appears to have only intensified since, as Shen (2011) reports that the price of neodymium has risen by 420% over a 12-month period beginning in July 2010. Political factors (e.g. trade embargo by China, which accounts for 90% of the world's supply of rare-earth metals) are undeniably affecting the market stability, but perhaps a more important factor is the increased demand for neodymium from other sectors. Gorman (2009) and Shen (2011) both note that increased demand of neodymium magnets for hybrid vehicles (as a part of electric motors) and wind turbines (as a part of generators) is causing the shortage of neodymium supply worldwide.

Opportunities and Next Steps for Technology

Researchers have investigated solid-state cooling technologies such as magnetic cooling for many years but are seeing recent improvements through technological breakthroughs in materials science and related fields. These advances can continue the development of the magnetic cooling cycle by increasing the achievable temperature lift, and reducing the cost of the magnetic materials. Assuming researchers can resolve the central issues relating to the paramagnetic materials, integration into HVAC equipment and field testing will reveal the capabilities of magnetic cooling.

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D.14 Microchannel Heat Exchanger

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Vapor Compression Heat Exchangers		0.31 Quads/yr	Commercially Available
Peak-demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Low	Lower Refrigerant Charge	Low	Medium

Description of Technology

Microchannel heat exchangers (MCHX) use small (<2mm) thin tubes connected parallel to two headers to facilitate heat transfer between air and refrigerant. Using MCHX increases the surface area of heat exchangers while reducing the volume of refrigerant and still maintaining capacity. MCHX has proven efficiency benefits, as it was originally designed for automobile air conditioners.

Description of How Technology Saves Energy

MCHXs increase the surface area to volume ratio over finned heat exchangers and shell and tube heat exchangers. MCHX increases heat transfer with less required space. Additionally, by meeting capacity requirements with less volume, microchannel depth is minimized, allowing the passing airflow to remain in the laminar flow.

Replacement Potential

MCHX can replace the heat exchanger of new HVAC equipment, but would unlikely replace heat exchangers in existing HVAC units.

Potential Scope of Impact

MCHX are suited for evaporators and condensers of central air conditioners and heat pumps. This technology could be installed in any climate in the U.S. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.31 Quads of electricity per year.

Energy Savings Performance

We estimate system energy savings to be 10% based on the following literature:

- Westphalen et al. (2003) estimated the total system energy savings of a unitary air conditioner with a MCHX to be 10%.

Cost Information

Based on the following literature, we estimate the cost of MCHX to be 50% of standard heat exchangers.

- Westphalen et al. (2003) estimated that the efficiency gains of MCHX result in a one to two-thirds cost reduction compared to a conventional heat exchanger.

Peak-demand Reduction and other Benefits Beyond Energy Efficiency Gains

Peak-demand reduction is estimated at 10%, proportional the estimated energy savings. MXHC significantly reduces refrigerant use compared to standard heat exchangers.

Technical Maturity and Recent Developments

This is a commercial available technology and is incorporated into products from many large HVAC manufacturers, including Trane, Carrier, and York.

Barriers to Market Adoption

Literature search did not find any barriers to market adoption.

Opportunities and Next Steps for Technology

Documenting energy savings of MCHX can help promote education of the technology.

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D.15 Mixed-Mode Conditioning

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Cooling and Ventilation		0.02 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Low	None	Low	High

Description of Technology

Mixed-mode conditioning combines mechanical cooling systems with ventilation systems to "provide acceptable comfort while minimize significant energy use," according to Gail Brager in the ASHRAE Journal (Brager 2006). Mixed-mode conditioning uses natural ventilation to perform cooling during feasible times and uses air-conditioning to supplement cooling when outdoor air temperatures are high. The natural ventilation is optimally automated. Passive and mechanical building systems can operate at the same time (concurrent), one at a time (changeover), or in different parts of the building (zoned).

Description of How Technology Saves Energy

Mixed-mode conditioning saves energy by using natural ventilation for cooling when cooling is preferred but air-conditioning is unnecessary. Therefore, mixed-mode conditioning saves off-peak cooling energy and fan energy using natural movement of air instead.

Replacement Potential

Mixed-mode conditioned is not suitable for retrofit because significant design work is required.

Potential Scope of Impact

Mixed-mode conditioning is a building strategy that could be designed into new residential buildings. Because mixed-mode conditioning uses unfiltered outside air, it would not be suitable in areas with high humidity, pollution, or noise levels. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.02 Quads of electricity per year.

Energy Savings Performance

We estimate mixed-mode conditioning could reduce cooling energy consumption by 20% based on the following literature:

Brager (2006) discussed the advantages of mixed-mode conditioning to improve occupant comfort and reduce building energy use. Energy savings vary from location to location but a 24.5% total savings was realized in a case study for commercial buildings.

Hu et al. (2007) found that buildings with mixed-mode conditioning would save 5-50% on yearly energy usage. They also noted that buildings only conditioned with ventilation air were impractical.

Anseeuw et al. (2008) examined a Vancouver community center constructed to use mixed-mode conditioning. An overall first year energy savings of 10% was found compared to models.

Although literature search did not provide information for residential buildings, we estimate residential buildings to save a similar amount.

Cost Information

Mixed-mode conditioning requires redundant systems for ventilation and cooling. Costs will vary with each project due to the building layout, occupancy, design, features, and climate.

NSF/IUCRC (2004) estimated the cost of implementing mixed-mode conditioning systems to be $5/sq.ft. for a new commercial construction.

Peak-demand Reduction and other Benefits Beyond Energy Efficiency Gains

Mixed-mode conditioning reduces energy during off-peak periods, thus, no peak-demand reduction is realized.

Technical Maturity and Recent Developments

Mixed-mode conditioning is emerging in the U.S. Currently, mixed-mode conditioning is not widely practiced, and the limited installations are commercial buildings. Literature search did not find any residential installations or case studies.

Barriers to Market Adoption

Having windows open often poses a security risk to the home. Additionally, open windows allow pollutants, noise, and insects into the home.

Opportunities and Next Steps for Technology

Mixed-mode conditioning would benefit from residential case studies to better understand the energy savings in residential applications.

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D.16 Night Sky Radiant Cooling

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Central Air Conditioners		0.01 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	N/A	Low	High

Description of Technology

Night sky radiant cooling (NSRC) provides cooling through heat loss by long-wave radiation from a building's roof to the night sky. Radiant cooling is accomplished a variety of ways:

- Essentially running a solar system in reverse; the cooler roof absorbs heat from piped water and releases it into the cooler air. The cool water is transferred into a storage tank for space cooling during the day, or returns through the building to absorb heat from the floor or indoor air.
- *Night Cool*, from the Florida Solar Energy Center at the University of Central Florida, uses a metal roof as a "low-mass highly conductive radiator" to perform sensible cooling (Parker 2008). The cooled air is stored in the attic, and as long as the attic temperature is lower than the indoor temperature, attic air supplements cooling.
- A night spray roof-storage system, called "NightSky", sprays water onto a roof during the night. The ambient air chills the water, which drains to a storage tank for cooling during the day (ORNL 1998).

How Technology Saves Energy

NSRC reduces cooling energy consumption by providing supplementary cooling. NSRC chills water or air during the night, which is stored for daytime use or used immediately to cool the home.

Replacement Potential

The NSRC is not easily installed and may require changing a roof layout or complete attic use. The NSRC will not replace a standard cooling system and requires supplemental cooling.

Potential Scope of Impact

A Night Sky Radiant Cooling system can supplement most cooling systems. NSRC can be installed in climates:

- With cooling for at least a few months of the year
- With clear nights
- With low humidity and,
- With large diurnal temperature differences.

Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.01 Quads of electricity per year.

Energy Savings Performance

Studies show that night sky radiant cooling systems can provide 15-70% of a commercial building's cooling requirements:

- A Davis Energy Group, Inc. Study in 1998 (over a one-week period from July 23-29) showed 70% energy savings in Vacaville, CA on a small commercial building. (ORNL 1998)

- Tests done for the *NightCool* (Parker 2008) concept at the University of Central Florida conclude a 15% cooling energy savings.

- A pilot of the WhiteCap™ system showed approximately 50% energy savings on a commercial building in Los Angeles. (Davis Energy Group 2012)

The wide range of savings is associated with climate and building configuration. We found no documentation of savings in residential applications, but we estimate a similar range.

Cost Information

The Davis Energy Group (2012) finds costs of a NSRC system to be between $8,500 and $10,100 for a small commercial building. Simple payback for these systems averaged about 2.5 years. We found no estimates for residential applications.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

Davis Energy Group, Inc. performed a week-long study in 1998 for ORNL. They claimed a peak-demand reduction of 87% in Vacaville, CA on a small commercial building from July 23-29 (ORNL 1998). We found no studies for residential applications, but expect that the reduction in monthly peak demand would be lower.

However, high temperatures at night (85°F+) prevent NSRC from providing sufficient cooling, and can lower the demand benefit.

Technical Maturity and Recent Developments

This is an emerging technology with limited commercial availability.

University of Central Florida and Cedar Mountain Solar Systems report pilots and research are ongoing, however, they have not disclosed further details.

Barriers to Market Adoption

NSRC is best for desert climates where the nighttime temperature is lower than 85°F; this limits the optimal areas for this technology.

Opportunities and Next Steps for Technology

Adding a dehumidification system may assist the NSRC in less optimal climates to expand possible market adoption beyond desert climates. We recommend verifying energy savings for NSRC studying viability for residential applications.

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D.17 Nighttime Ventilation Cooling

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Conventional cooling systems		0.01 Quads/yr	Commercially Available
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Improved comfort, IAQ	Low	Medium

Description of Technology

For HVAC systems, a building's thermal mass stores heating or cooling energy over time, slowing temperature changes caused by the difference between outdoor and indoor air temperatures. For a residential structure, the thermal mass consists of the building materials, foundation, furniture, enclosed air, etc., located within the home. During hot days, pre-cooling this thermal mass during nighttime or early-morning hours can reduce air-conditioning energy consumption. Rather than running the conventional air-conditioning system, outdoor is circulated throughout the home for pre-cooling. A nighttime ventilation cooling system opens a damper in the air handler that brings low-temperature outdoor air to the indoor space through an exterior vent. The system can operate automatically using an algorithm that predicts temperatures for the next day based on weather conditions.

How Technology Saves Energy

During the warmer months, circulating low-temperature nighttime air throughout a house cools the home so that when outdoor temperatures rise, the indoor temperature remains cool longer. A nighttime ventilation system reduces the need for conventional air conditioning during the day, lowering the daily energy consumption associated with cooling the residence. Energy is saved by offsetting the overall need for conventional cooling and limiting DX system operation during the hottest part of the day, when efficiency is lowest.

Replacement Potential

Although this technology could be retrofit into certain buildings, developers envision nighttime ventilation systems primarily for new construction.

Potential Scope of Impact

Nighttime ventilation systems displace the energy consumption of conventional air-conditioning equipment in homes using central cooling. Energy savings for this technology varies across climate regions, but becomes more efficient than DX cooling when peak daytime temperatures are greater than 92 ˚F. Because high summertime temperatures typically coincide with high nighttime humidity for much of the U.S., we estimate energy savings only for dry regions. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.01 Quads of electricity per year.

Energy Savings Performance

Hoeschele (2011) tested the SmartVent and NightBreeze nighttime ventilation cooling systems in a number of homes in California. When used throughout the cooling season, the systems performed on par or worse than DX cooling systems. When activated only for days where the peak temperature was greater than 92 ˚F, the systems reduced energy consumption by 14% (SmartVent) and 30% (NightBreeze).

PIER (2005) estimates that the NightBreeze nighttime ventilation system could achieve 15-35% seasonal energy savings when applied with the correct control scheme.

Cost Information

For new construction, PIER (2005) estimates an incremental cost of $1000 for the SmartVent and $1500 for the NightBreeze systems. In areas with time-of-use electric rates, nighttime ventilation systems provide additional cost savings.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

Because these systems work most effectively during the hottest parts of the year, nighttime ventilation cooling has a very high potential for peak-demand savings. These systems provide more ventilation in the home, which can improve comfort and IAQ.

Technical Maturity and Recent Developments

This is a commercially available technology. Advance Energy Products Corp. markets their NightBreeze system which integrates into the conventional HVAC system of a home. Beutler Corp. manufacturers SmartVent which is a simpler dedicated ventilation system.

Barriers to Market Adoption

This technology has not been tested across a variety of regions and climate types to accurately determine best practices and energy savings. High nighttime humidity would prevent the application of this type of system. Because these systems require changes to the duct systems, it is not easy to retrofit. Because nighttime ventilation systems consume significant amounts of energy during the night, the cooling demand for a certain day must be high to realize any energy savings.

Opportunities and Next Steps for Technology

Besides gaining a better understanding of where this technology would be applicable, improving the predictive control scheme would increase energy savings. Currently, the advanced controls of the NightBreeze rely on a temperature pattern with a predictive algorithm to anticipate the following day’s temperature profile. This could be enhanced by connecting the controls to actual weather forecasts over the internet. Increasing the efficiency of the nighttime ventilation system would increase its use for days reaching lower than 92 ˚F.

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D.18 Quality Installation

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Residential HVAC Systems		1.14 Quads/yr	Commercially Available
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Medium	Improved comfort, equipment lifetime	High	Medium

Description of Technology

For HVAC equipment to operate as expected, proper installation and startup is essential. The homeowner's significant investment into premium equipment can be wasted if the system does not operate as efficiently as intended. Improper installation can result in incorrect equipment sizing, leaky duct systems, improper refrigerant charge, and poor airflow over heat exchangers. To reduce the frequency of poor installation, various residential HVAC stakeholders including contractors, equipment manufacturers, industry experts, utilities, and building owners have developed quality-installation specifications and certification programs. While quality-installation standards are designed for residential and light-commercial systems, this practice is generally referred to as commissioning for larger multi-family buildings.

Building on earlier CEE guidelines, the ACCA established their Standard 5 QI-2010 specification on quality installation, and the accompanying Standard 9 QIvp-2011 covering verification protocols for quality installation. These two documents identify and establish minimum requirements for quality installation in residential systems in the following areas:

- **Design** - ventilation, building heat-gain/loss load calculations, proper equipment capacity selection, geothermal-heat-pump ground heat exchanger, matched systems
- **Distribution** – duct leakage, airflow balance, hydronic balance
- **Equipment Installation** – air/water flow through heat exchangers, refrigerant charge, electrical requirements, on-rate for fuel-fired systems, combustion venting system, system controls
- **System Documentation and Owner Education** – proper system documentation to the owner, owner/operator education.

How Technology Saves Energy

By establishing guidelines and standards, contractors can train and certify their technicians to perform quality residential HVAC installations that help ensure efficient performance. Quality installation aims to eliminate inefficient performance associated with common installation problems.

Replacement Potential

Quality installation standards can be used for all retrofit installations.

Potential Scope of Impact

Although the current quality installation standards are aimed at air conditioners, heat pumps, and furnaces, the principles could be applied to almost all HVAC systems.

Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.59 Quads of natural gas, and 0.55 Quads of electricity per year.

Energy Savings Performance

Energy savings from quality installation are in addition to the savings attributed to high-efficiency equipment.

Leopkey (2008) discussed that over half of air-conditioner installations performed poorly due to installation issues, with losses in system efficiency of over 30%. Through quality installation, the average system could save 1300-1900 kWh/year, and reduce peak demand by 1.0-1.3 kW/ year.

Foster et al. (2002) presented their findings on different quality installation initiatives, concluding that overall savings of up to 35% and demand savings of 1.5 kW could be achieved through quality installation.

ENERGY STAR (2012) claims that quality installation programs could save 18-36% for air conditioners and heat pumps, and 11-18% for furnaces.

Cost Information

Installations using contractors certified for quality installation could carry a premium over those who do not, but energy savings should payback this premium quickly. Utility and government incentives are available in some regions to help defray the increased installation cost. By correctly sizing equipment to the building load, Foster et al. (2002) typically saw a decrease in equipment size by ½ ton, reducing cooling equipment costs.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

By ensuring cooling equipment operates as intended, quality installation can lower the peak demand for a home. Resolving many of the issues associated with poor installation also can increase equipment lifetimes, and can improve occupant comfort.

Technical Maturity and Recent Developments

This is a commercially available technology. The ACCA quality-installation standards are available for contractor use themselves, and ENERGY STAR has developed a program looking for utility and government partners to start certification and verification programs across the U.S. The program will provide training and promotional tools to contractors, develop a list of qualified contractors by region, and verify contractor installations through commissioning forms, load calculations, and site visits.

Barriers to Market Adoption

Contractors commonly replace equipment with the same size and without performing additional calculations, partly to avoid customer dissatisfaction on the hottest/coldest time of the year if the system underperforms. Oversized equipment can also cover up many of the issues caused by poor installation and maintenance practices. Customers may expect and assume that contractors will perform installations correctly, and may be unaware of the frequency of problems associated by poor performance. If the customer does not experience any changes in comfort, they may assume the system is operating as intended. Competitive pressures often limit the amount of time/money a contractor spends verifying performance after an installation. Manufacturers have traditionally been willing to honor warranties for equipment that failed due to poor installation.

Opportunities and Next Steps for Technology

Increasing customer and contractor awareness of quality installation standards may lead to wider acceptance in the industry. Contractors can differentiate themselves from the competition by participating in local programs sponsored by ENERGY STAR quality installation initiatives. Nevertheless, many companies serving residential customers are small businesses and may not be able to devote the time and resources required to implement a quality-installation program. Documenting and showcasing businesses that have successfully incorporated quality-installation practices could facilitate participation from more contractors, and the wider industry. .

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D.19 Seasonal Thermal Energy Storage

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Unitary HVAC equipment		0.09 Quads/yr	Emerging
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	None	Low	High

Description of Technology

Thermal energy storage (TES) allows heating and cooling loads to be met by low-cost energy produced at a different time. According to Roth and Brodrick in an ASHRAE Journal article, two primary timescales of TES exist: diurnal and seasonal. Diurnal systems produce ice or chilled water in anticipation of large cooling loads or store heat in thermal mass in anticipation of heating loads. Seasonal TES stores thermal energy from summer for use in the winter, and vice versa. Seasonal TES use a variety of storage techniques, including (Roth, 2009):

- Aquifer Storage, which uses groundwater via wells to transfer heat. Typically, aquifer TES will have one hot and one cold pool for heat transfer.
- Borehole Storage, which uses holes drilled deep (35-200m) into the ground. The holes are filled with a thermally conductive material and a liquid solution is pump through the boreholes to transfer heat in the required direction.
- Cold-storage pits, which store snow in northern climates to be used during the cooling season. The snow is covered and insulated, and as it slowly melts, the cold water is pumped through the building for cooling.

Diurnal TES does not provide quantifiable energy savings; only peak-demand reductions by using off-peak electricity to cool on-peak loads. Therefore, we will only examine seasonal TES in this report.

Description of How Technology Saves Energy

TES uses low cost, typically wasted, energy (solar, snow, outdoor air-temperatures) to transfer energy for use during high cost/high demand times. These thermal sources replace required primary energy (gas, oil, electric) with low-cost renewable resources.

Replacement Potential

TES systems typically require large excavations or storage containers, prohibiting retrofits for most residential applications.

Potential Scope of Impact

Seasonal TES is better suited in locations with large variations in seasonal temperature; typically found in the northern U.S. Seasonal TES primarily applies to new construction applications. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.05 Quads of natural gas, and 0.04 Quads of electricity per year.

Energy Savings Performance

We estimate seasonal TES would save approximately 30% of heating energy and 70% of cooling energy based on the following literature:

- Paksoy et al. (2004) claim that seasonal TES reduces energy use by 20-30% for heating and 60-80% for cooling in large commercial applications.
- Zizzo and Kennedy (2010) claim that seasonal TES systems in the Toronto area would reduce energy use by 30-40% for space and water heating.

Cost Information

Although literature search did not provide any cost information for residential systems, based on the following, we estimate seasonal TES costs to be prohibitive for residential applications.

Roth and Brodrick (Roth, 2009) discuss how economics vary with the size and utilization of the seasonal TES system. Per-unit cost of the system decreases as both size and percentage of yearly energy use increases. The stored energy cost 2-20 times higher than natural gas.

Peak-demand Reduction and other Benefits Beyond Energy Efficiency Gains

Peak-demand would be reduced significantly because energy stored over the season would directly be used to reduce peak energy consumption. Zizzo and Kennedy (2010) claim that peak demand of cooling systems can be reduced by 80-90% for commercial applications.

Technical Maturity and Recent Developments

This is an emerging technology with limited availability in the U.S. market today. Seasonal TES have been installed for commercial applications throughout Europe and in limited applications in the U.S. For residential applications, one known seasonal TES solution is Thermal Storage Solutions out of Vermont. They provide little detail on their technology because of a pending patent.

Barriers to Market Adoption

High first cost significantly prohibits the adoption of seasonal TES. Additionally, the lack of contractor resources and high system complexity limit market growth potential.

Opportunities and Next Steps for Technology

We recommend research into whether seasonal TES will provide costs or benefits to justify further research.

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D.20 Smaller Centrifugal Compressors

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Multi-family buildings using lower capacity chillers (25-80 tons)		0.04 Quads/yr	Commercially Available
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	Improved control, noise reduction	Medium	Medium

Description of Technology

Centrifugal chillers provide the most efficient cooling for vapor-compression chilled-water systems for larger buildings. Centrifugal compressors typically are used for systems with cooling loads over 100 tons, and reciprocating, scroll, and screw compressors make up the small chiller market. Small, oil-free centrifugal compressors bridge this gap and offer an energy-efficient technology for the low-tonnage chillers seen in many multi-family buildings. The typical small centrifugal compressor consists of centrifugal impellers, a permanent-magnet synchronous motor, magnetic bearings, and variable-speed drive. These innovative components combine to provide capacity modulation and energy efficiency, with less vibration and noise, in a compact unit.

How Technology Saves Energy

The high-performance components of the small centrifugal compressor allow it to achieve higher efficiencies than a baseline reciprocating chiller. The variable-speed drive controls the compressor output to better match part-load conditions. The direct-drive configuration with magnetic bearings replaces mechanical gears and linkages, raising efficiency by connecting the centrifugal impeller directly with the motor.

Replacement Potential

This technology can be retrofit onto existing chiller systems or be implemented as a component in high-efficiency packaged chillers. For residential applications, this technology would only apply to large multi-family buildings. Even for these cases, buildings not originally designed with chilled water systems typically do not convert in a retrofit project.

Potential Scope of Impact

Small centrifugal compressors would replace reciprocating and screw compressors for chilled-water systems in the 25-80 ton range. Because of the capacity requirements of these chillers, only large multi-family residential buildings using central cooling systems would benefit from this technology. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.04 Quads of electricity per year.

Energy Savings Performance

Erpelding and Moman (2005) examined the installation of Danfoss Turbocor compressors in the California market, which realized a 30-50% reduction in yearly energy usage. Citing the manufacturer's material, the small centrifugal compressor had efficiencies 30%, 33%, and 40% above those for other centrifugal, screw, and reciprocating compressors, respectively.

Dieckmann et al. (2003) estimated a total energy savings of 15% for small centrifugal compressors and much higher efficiencies in part-load situations.

Danfoss (2011) advertises a part-load improvement of 33%, a 10-40% demand reduction, and a 40% total energy savings for certain installations.

Cost Information

Erpelding and Moman (2005) cite incremental cost increases of 33%, 45% and 15% over other commercially available centrifugal, screw, and reciprocating compressors, respectively.

Dieckmann et al. (2003) note that 75% of the system costs for the small centrifugal compressors consists of the high-speed motor and variable-speed drive. Both of these technologies have reduced costs in recent years.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

Small centrifugal compressors have controllable capacity due to the variable-speed drive and have reduced noise and vibration compared to other compressors.

Technical Maturity and Recent Developments

This is a commercially available technology in capacities between 25 and 80, although lower capacities may be possible through further development. Danfoss has been marketing its Turbocor small centrifugal compressor since the early 2000s, both for field replacements of compressors and for new chillers offered by other manufacturers.

Barriers to Market Adoption

Only the largest residential buildings could benefit from chiller compressor replacement. Even then, chiller usage in existing buildings is low. First cost for centrifugal compressors, and chiller systems as a whole, is always an issue. Manufacturers of packaged chillers driven by reciprocating or screw compressors may resist introducing products with small centrifugal compressors because of the significant development costs and that the new products would cut into their current offerings.

Opportunities and Next Steps for Technology

Further development of packaged chillers utilizing the small centrifugal compressors will help bring the optimized systems to market. The technical maturity of variable-speed drives and high-speed motors will reduce their costs and make the small centrifugal compressor system more economical.

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D.21 Smart Ventilation Systems

<table>
<tr><th colspan="2">Systems Impacted by Technology</th><th>Energy Savings Performance</th><th>Technical Maturity</th></tr>
<tr><td colspan="2">Residential HVAC Systems</td><td>0.03 Quads/yr</td><td>Commercially Available</td></tr>
<tr><th>Peak-Demand Reduction Potential</th><th>Non-Energy Benefits</th><th>Ease of Replacement</th><th>Cost/ Complexity</th></tr>
<tr><td>Low</td><td>Improved IAQ, comfort</td><td>Low</td><td>Medium</td></tr>
</table>

Description of Technology

Energy-efficient building practices have decreased the amount of heating and cooling needed in a residential home by improving building envelopes, adding insulation, reducing solar heat gain, using low-wattage lighting, etc. Traditionally, air infiltration through cracks around windows or small openings in exterior walls provided ventilation to the home at the expense of heating and cooling energy. Tighter building envelopes decrease heating and cooling losses, but reduce infiltration significantly (up to 3-4 times less), leaving the indoor space under-ventilated. Mechanical ventilation systems use fans to supply the indoor space with fresh outdoor air and exhaust stale, contaminated air resulting in suitable indoor conditions. Two smart ventilation systems have been shown to decrease ventilation energy consumption for residential buildings:

- Demand ventilation systems use sensors to monitor indoor humidity and/or CO_2 levels and supply outdoor air only when indoor conditions exceed certain thresholds. This strategy maintains appropriate IAQ with minimal outdoor airflow, limiting ventilation energy consumption.
- Energy-recovery units capture the heating or cooling energy of the exhaust airstream and precondition the incoming outdoor air through a heat exchanger. Reducing the temperature and humidity difference between outdoor and indoor conditions minimizes the additional energy requirement to condition the outdoor air. Energy recovery ventilators (ERV) exchange both heat and moisture, whereas heat recovery ventilators (HRVs) only exchange heat. These systems typically utilize desiccant wheels, or solid heat exchanger cores.

How Technology Saves Energy

For energy-efficient buildings, heating and cooling energy consumption decreases while ventilation demands increase to meet suitable indoor conditions. Minimizing the additional energy consumption due to ventilation requires either decreasing the amount supplied outdoor air or the energy required to condition the outdoor air through exhaust energy recovery. Both of these methods provide appropriate IAQ using less energy than conventional ventilation strategies.

Replacement Potential

While smart ventilation systems integrate more easily for new-construction projects designed to accommodate the additional controls and equipment, existing homes can benefit as well. For existing homes undergoing major upgrades to the seal the building envelope , incorporating smart ventilation systems is probably feasible.

Potential Scope of Impact

New and existing homes with tight building envelopes to minimize thermal losses and a need for mechanical ventilation would benefit from smart ventilation systems. Because these systems reduce the additional thermal energy requirements caused by the increased ventilation demand, they are applicable for all heating and cooling equipment types.

Because most homes in the U.S. do not require dedicated ventilation systems, this technology option currently has limited applicable energy consumption. As building codes drive the national housing stock to have tighter envelopes, the energy consumption associated with ventilation within homes will increase, and smart ventilation systems would have a greater technical energy savings potential. Based on an analysis of its potential impact on HVAC systems in the U.S. today, this technology would save 0.01 Quads of natural gas, and 0.02 Quads of electricity per year.

Energy Savings Performance

A literature search identified several energy savings estimates, all of which are compared to a home using continuous ventilation with no energy recovery:

- Mortensen et al. (2008) studied the indoor conditions and energy consumption associated with ventilating an apartment building. They found that demand ventilation could result in 8-10% system energy savings.

- Van Den Bossche et al. (2007) determined that a demand-ventilation system monitoring humidity and CO_2 levels could save over 10%.

- Minnesota Sustainable Housing Initiative (2011) determined that 80% efficient energy-recovery systems could save 10-15% of heating and cooling energy consumption.

Cost Information

For demand ventilation, the additional cost of the system depends on the number and complexity of the humidity and/or CO_2 sensors. CO_2 sensors used for commercial applications cost $200-300 each-humidity sensors cost significantly less. Payback will vary depending on the ventilation demand and occupancy schedule, but attractive paybacks have been demonstrated in commercial systems (Esource 2005).

Minnesota Sustainable Housing Initiative (2011) states that ERV and HRV systems have an approximate installed cost of $1,200-1,500. Economics are better in regions with heating or cooling extremes compared to mild climates.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

Smart ventilation systems lower peak demand by reducing the electricity consumption to condition and delivery outdoor air, especially during the cooling season. Having a dedicated ventilation system generally increases IAQ and occupant comfort.

Technical Maturity and Recent Developments

This is a commercially available technology. Many manufacturers market ERV and HRV systems throughout North America, and they are more common in colder climates. Demand ventilation systems are more common in commercial buildings, but the sensors are available for residential applications.

Barriers to Market Adoption

Smart ventilation systems are more easily incorporated into new construction or major renovations, which can limit their application. The additional ductwork and space needed for energy-recovery systems adds some complexity, especially for homes that have air handlers in tight spaces. Some building codes do not permit non-automatic ventilation strategies, which would limit the application of demand ventilation systems. Programming the demand ventilation system to circulate air to meet minimum hourly air change requirements may meet code requirements, but would reduce savings.

Opportunities and Next Steps for Technology

Incorporating energy-recovery systems into retrofit air handlers would decrease the installation costs and complexity for existing buildings. Developing models that better predict the energy savings and costs of energy-recovery systems across geographic regions would increase homeowner awareness and decrease the sticker shock of such systems. Field studies of homes located in various climate regions using demand ventilation with different occupancy patterns would point to the most promising applications.

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D.22 Swimming-Pool Heat Sink

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Central Air Conditioners		0.01 Quads/yr	R & D
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
High	None	Low	High

Description of Technology

A swimming-pool heat sink uses a swimming pool to dump the waste heat of central air conditioner condensers. A central air conditioner using a water-cooled condenser with a tube-in-tube design would reject heat directly to pool water flowing around the refrigerant tubes.

How Technology Saves Energy

According to researchers at UC Davis (2012), the swimming-pool heat sink reduces the required heat transfer temperature difference; using air requires a 35°C temperature difference, but using water requires 20°C. Therefore, CACs can realize higher efficiencies at higher outdoor temperatures. Additionally, rejecting heat to the swimming pool reduces energy consumption for pool heating.

Replacement Potential

A swimming-pool heat sink would unlikely be retrofitted into an existing home. This technology could be added into the design of a new home.

Potential Scope of Impact

A swimming-pool heat sink would work best in warmer and drier climates, according to researchers at UC Davis (2012). Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.01 Quads of electricity per year.

Energy Savings Performance

We estimate this technology could reduce a home's cooling consumption by 30% based on:

- UC Davis (2011) estimates 30% cooling consumption savings for a swimming-pool heat sink.

Cost Information

Literature search did not produce any cost information.

Peak-demand Reduction and other Benefits Beyond Energy Efficiency Gains

UC Davis researchers (2011) estimate peak-demand reduction of 30-35%.

Technical Maturity and Recent Developments

The swimming-pool heat sink is currently under development. Researchers at UC Davis (2011) completed a second round of experiments and validated their modeled energy savings for a variety of California climate zones. UC Davis (2011) is creating a tool to assist contractors with sizing pools taking into account air conditioner size and pool shading.

Barriers to Market Adoption

With a pool-water-cooled condenser, there is a risk of potential refrigerant leaks into the pool. Additionally, the pool may be unusable if the pool overheats.

Opportunities and Next Steps for Technology

We recommend monitoring progress and data of the swimming-pool heat sink to determine viability.

References

Kraemer, Susan. 2010. "Could A/C Units Vent Heat to a Swimming Pool? You Tell Me." CleanTechnica.com. September 15, 2010.

UC Davis. 2011. "Annual Report 2010-2011." Western Cooling Efficiency Center. September 12, 2011.

UC Davis. 2012. "Swimming Pools as Heat Sinks for Air Conditioners." Western Cooling Efficiency Center." January 17, 2012

D.23 Variable-Stroke Compressor

Systems Impacted by Technology		Energy Savings Performance	Technical Maturity
Central Air Conditioners and Heat Pumps		0.92 Quads/yr	R & D
Peak-Demand Reduction Potential	**Non-Energy Benefits**	**Ease of Replacement**	**Cost/ Complexity**
Medium	None	Low	Medium

Description of Technology

Beard and Pennock (1988) introduced the Beard-Pennock Variable-Stroke Compressor , a variable-stroke compressor that controls pumping volume by adjusting the ground link essentially change the length of the connecting rod.

Groll and Kim (Groll-2 2006) proposed an improved design called the "bowtie compressor", seen in Figure D.23-1. The bowtie compressor improves upon the BPC by reciprocating the piston axially, not linearly, while rotating the crankshaft counter-clockwise, thus causing two simultaneous compressions. The cylinder of the compressor is in a sliding chamber to change the position of the piston rod, which solely modulates the capacity.

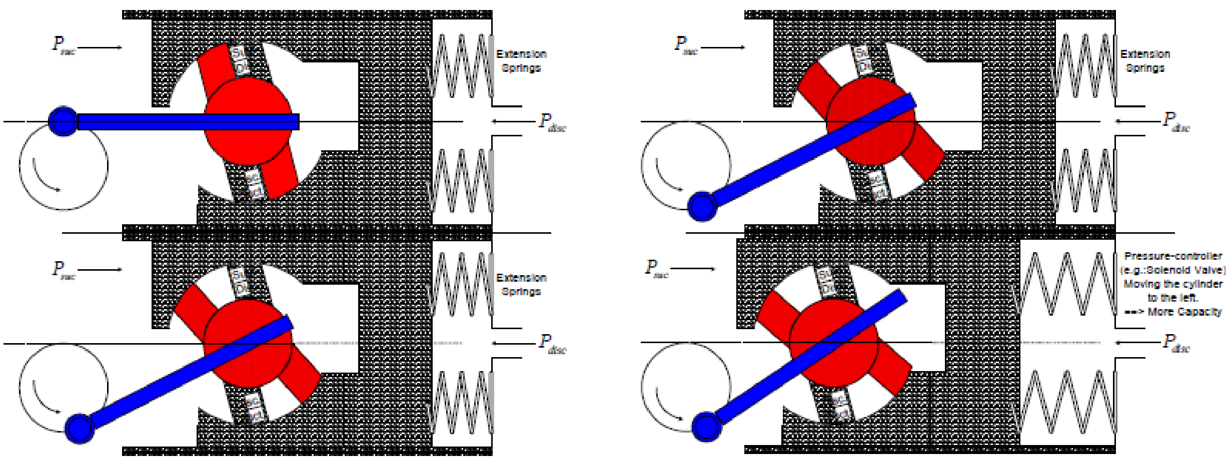


Figure 1: Diagram of the proposed design.

Figure 2: Diagram showing how the piston stroke changes.

Figure D.23-1. Diagrams of the Variable-Stroke Compressor Reciprocating Axially.

Source: Groll and Kim (Groll-2 2006)

How Technology Saves Energy

The variable-stroke compressor modulates capacity by adjusting the length of the piston rod as opposed to changing the motor speed. By reducing capacity, the variable-stroke compressor reduces consumption when full load is unnecessary.

Replacement Potential

Variable-stroke compressors can be incorporated into residential air conditioners and heat pumps, and readily installed when equipment is replaced. Variable-stroke compressors are not readily retrofit into existing equipment.

Potential Scope of Impact

The variable-stroke compressor could replace compressors in many residential (and commercial) central heat pumps and air conditioners. The VSC would apply to units across all climate zones. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.92 Quads of electricity per year.

Energy Savings Performance

We estimate the variable-stroke compressor can reduce heat pump and air conditioning energy consumption by 20%, according to a phone call with the Eckhard Groll, co-inventor of the bowtie compressor (Groll 2012)

Cost Information

Eckhard Groll (2012) claims, if manufactured, costs would be competitive with current variable-speed compressors.

Peak-Demand Reduction and other Benefits Beyond Energy Efficiency Gains

The variable-stroke compressor would reduce peak-demand proportionally to estimated energy savings.

Technical Maturity and Recent Developments

This technology is currently in development and required additional research for a prototype. Eckhard Groll, in a phone call (Groll 2012), noted that research is currently on hold due to lack of a manufacturer partner.

Barriers to Market Adoption

Literature search did not reveal any barriers for variable-stroke compressors.

Opportunities and Next Steps for Technology

Groll and Kim have not made public any further research plans. We recommend studying the viability of the variable-stroke compressor.

References

Beard, J.E. et Pennock, G.R. 1988. "The Beard-Pennock Variable-Stroke Compressor" Retrieved from http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1675&context=icec.

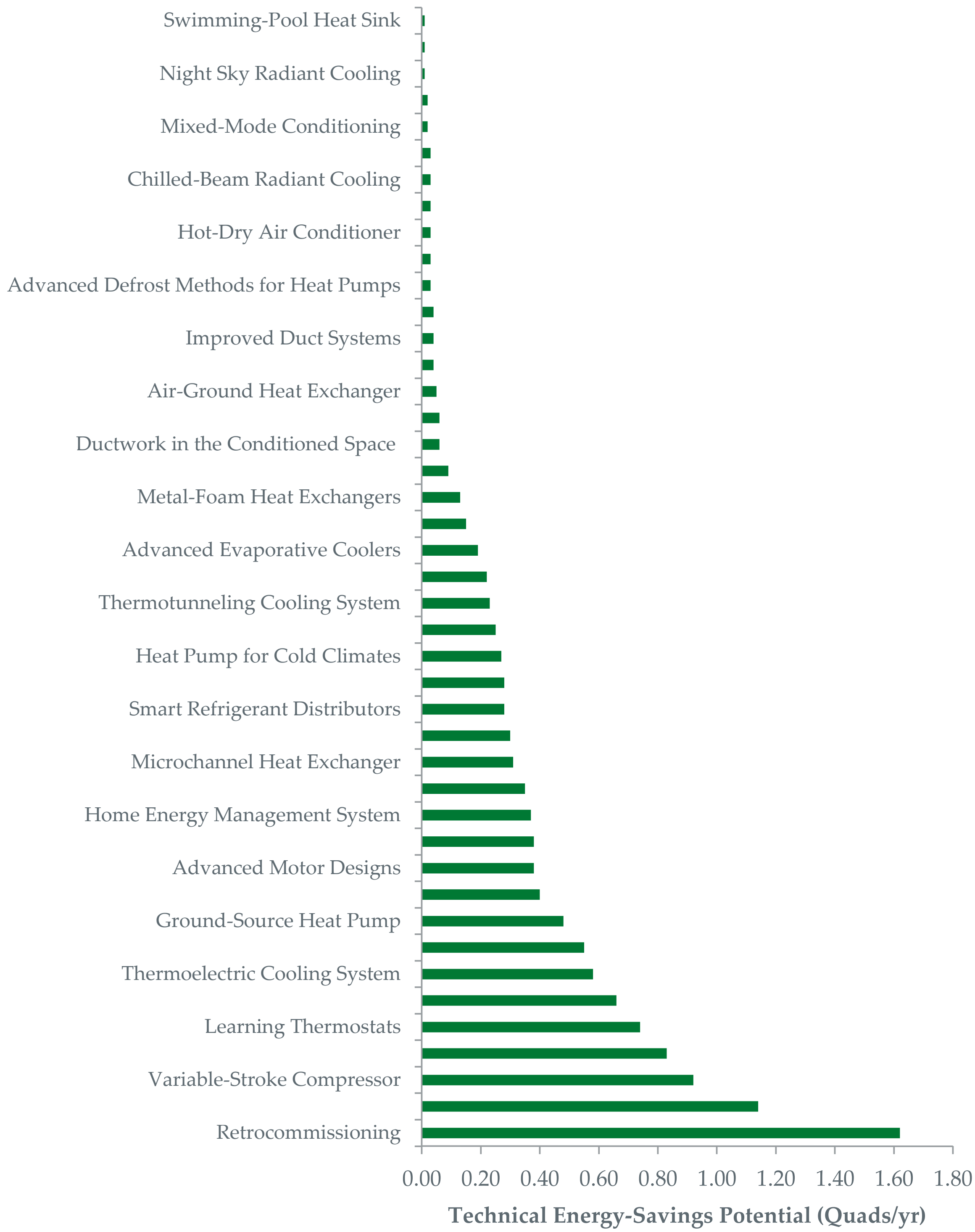
(Groll-1) Groll, Eckhard. 2006. "Compressor Research at the Ray W. Herrick Laboratories." Retrieved from http://www.sjtuirc.sjtu.edu.cn/06cerebration/report/E.A.Groll.pdf .

(Groll-2) Groll, Eckhard et Kim, Junhyeung. 2006. “Bowtie Compressor With Novel Capacity Modulation Part 1: Design Description and Model Development” < http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2779&context=icec >, 2006.

(Groll-3) Groll, Eckhard et Kim, Junhyeung. 2006. “Bowtie Compressor With Novel Capacity Modulation Part 2: Model Validation and Parametric Studies” <http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=2780&context=icec >, 2006.

Groll, Eckhard. 2012. Phone call with Eckhard Groll. January 13, 2012

Appendix E Technical Energy Savings Potential of the 42 Technology Options



Note: Potential savings are not additive for most technology options and applications.

Appendix F Scoring Results for the 42 Technology Options

Technology Name	Technical Energy Savings Potential (35%)	Fit with DOE BT Mission (30%)	Cost/Complexity (15%)	Other Non-Energy Benefits (15%)	Peak-Demand-Reduction Potential (5%)	Overall Score
Gas Engine-Driven Heat Pump	5	4	2	4	5	**4.10**
Thermoelectric Cooling System	5	4	2	4	2	**3.95**
Gas-Fired Absorption Heat Pump	5	5	2	2	1	**3.90**
Learning Thermostats	5	4	3	2	2	**3.80**
Regular Maintenance	5	3	3	3	2	**3.65**
Retrocommissioning	5	3	2	4	2	**3.65**
Integrated Heat Pump	5	2	2	4	1	**3.30**
Thermoelectrically Enhanced Subcoolers	4	3	2	4	2	**3.30**
Geothermal Heat Pump	4	4	2	2	2	**3.30**
Hybrid Geothermal Heat Pump	4	4	2	2	2	**3.30**
Ductless Multi-Split System	4	3	3	3	1	**3.25**
Smart Ceiling-Fan Controls	4	3	4	2	1	**3.25**
Aerosol Duct Sealing	4	3	2	3	3	**3.20**
Home Energy Management System	4	4	2	1	3	**3.20**
Smart Refrigerant Distributors	4	2	3	4	1	**3.10**
Thermotunneling Cooling System	3	4	1	4	2	**3.10**
Heat Pump for Cold Climates	4	3	2	3	1	**3.10**
Central A/C and Heat Pump FDD	4	2	3	3	2	**3.00**
Brushless Direct-Current Motors	4	3	3	1	2	**3.00**
Quality Installation*	5	1	3	3	2	**3.05**
Advanced Evaporative Coolers	3	3	2	3	5	**2.95**
Variable-Stroke Compressor	5	1	2	3	2	**2.90**
Microchannel Heat Exchanger	4	2	3	2	1	**2.80**
Evaporative Roof Cooling	3	3	3	1	5	**2.80**
District Heating and Cooling	2	4	1	2	5	**2.60**
Improved Duct Systems	1	4	4	2	2	**2.55**
Magnetic Cooling System	4	2	1	2	2	**2.55**
Airflow-Optimizing System	1	3	3	4	2	**2.40**
Hot-Dry Air Conditioner	1	3	4	2	5	**2.40**
Evaporatively Cooled Condensers	1	3	2	3	4	**2.20**
Ductwork in the Conditioned Space	2	2	3	2	2	**2.15**
Nighttime Ventilation Cooling	1	2	3	3	5	**2.10**
Advanced Defrost Methods for Heat Pumps	1	2	3	4	1	**2.05**
Mixed-Mode Conditioning	1	3	3	2	1	**2.05**
Air-Ground Heat Exchanger	2	2	1	2	4	**1.95**
Seasonal Thermal Energy Storage	2	2	1	1	4	**1.80**
Chilled-Beam Radiant Cooling	1	2	3	2	1	**1.75**
Smart Ventilation Systems	1	2	2	3	1	**1.75**
Liquid-Desiccant Air Conditioner	1	2	1	3	2	**1.65**

Night Sky Radiant Cooling	1	2	1	1	5	**1.50**
Smaller Centrifugal Compressors	1	1	2	3	1	**1.45**
Swimming-Pool Heat Sink	1	1	2	2	2	**1.35**

* Technology options that scored a 1 for 'Technical Energy Savings Potential' or 'Fit for DOE BT Mission' were not considered for in-depth analysis. As a result, Quality Installation did not pass the second screening despite its overall score.

Appendix G In-Depth Analyses of the 19 Priority Technology Options

As discussed in Section 3, we performed an in-depth analysis for each of the 19 technology options we selected after the second round of screening. This appendix consists of the in-depth analyses for the 19 priority technology options, organized by category[13], as presented in Table G-1.

Table G-1. Priority Technology Options by Category

Category	Applicable Technology Options
Advanced Component Technology Options	Brushless Direct-Current Motors Metal-Foam Heat Exchangers Smart Refrigerant Distributors
Alternative Heating and Cooling Technology Options	Gas-Fired Absorption Heat Pump Thermoelectric Cooling System Thermoelectrically Enhanced Subcoolers Thermotunneling Cooling System
Advanced Heat Pump Technology Options	Ductless Multi-Split System Gas Engine-Driven Heat Pump Geothermal Heat Pump Heat Pump for Cold Climates Hybrid Geothermal Heat Pump Integrated Heat Pump
High-Performance System Design and Restoration Technology Options	Aerosol Duct Sealing Regular Maintenance Retrocommissioning
Intelligent Controls and Diagnostic Technology Options	Central A/C and Heat Pump Fault Detection and Diagnostics Home Energy Management System Learning Thermostat Smart Ceiling-Fan Controls

Each analysis contains the following subsections:

- **Overview table:** Brief tabular description of the technology option, the estimated technical energy savings potential and three-step ratings (High, Medium, Low) of the technology's market readiness and its estimated cost/complexity.
- **Summary:** Overview of the technology option.
- **Background:** How the technology works, its practical uses, its technical maturity/current developmental status, its barriers to market adoption, and why the technology offers an efficiency improvement over conventional technologies.

[13] Category descriptions are found in Section 3.

- **Energy Savings Potential:** The technology's estimated energy savings based on technically reasonable level of penetration.
- **Cost and Complexity:** The estimated installed cost of the technology and factors that may increase or decrease the complexity of HVAC system operation and maintenance.
- **Peak-Demand Reduction and Other Non-Energy Benefits:** The technology's estimated ability to reduce electrical demand during peak hours and provide benefits beyond HVAC energy savings.
- **Next Steps for Technology Development:** What needs to be done to commercialize the technology further.
- **References:** References consulted during our investigation.

G.1 Advanced Component Technology Options

G.2 Brushless Direct-Current Motors

<table>
<tr><th>Brief Description</th><td colspan="2">Brushless direct-current (BLDC) motors use electronic controls to control speed and reduce energy losses, improving efficiency.</td></tr>
<tr><th>Technical Energy Savings Potential</th><th>Technical Maturity</th><th>Cost/Complexity</th></tr>
<tr><td>0.38 Quads/year</td><td>Emerging</td><td>Medium - High</td></tr>
</table>

Table G.1.1-1 summarizes brushless direct-current motors for residential HVAC equipment.

Table G.1.1-1. Summary of the Characteristics of Brushless Direct-Current Motors

<table>
<tr><th colspan="2">Attribute</th><th>Value</th><th>Comments</th></tr>
<tr><td rowspan="4">Technology Characteristics</td><td>Equipment Type to which Technology is Most Applicable</td><td>All HVAC</td><td></td></tr>
<tr><td>Fuel Type</td><td>Electricity</td><td></td></tr>
<tr><td>Technical Maturity</td><td>Emerging</td><td></td></tr>
<tr><td>Most Promising Applications</td><td>Variable-Speed CACs and HPs</td><td></td></tr>
<tr><td rowspan="4">Energy Savings Estimate</td><td>Baseline Technology (Current Technology that would be Displaced)</td><td>75% efficiency AC induction motor</td><td>75% is a rough average of DOE minimum standards for HVAC sized (1/4-1/2 HP) blower motors.</td></tr>
<tr><td>Annual Energy Consumption of Baseline Technology</td><td>8.12 Quads/year</td><td></td></tr>
<tr><td>Applicability to Replacement Market</td><td>High</td><td>Motors in current or replacement heat pumps Could also replace blower fan motors for existing furnaces, air conditioners, or heat pumps.</td></tr>
<tr><td>Technical Energy Savings Potential</td><td>0.38 Quads/year</td><td></td></tr>
<tr><td rowspan="2">Other Benefits</td><td>Potential for Peak-Demand Reduction</td><td>Medium</td><td></td></tr>
<tr><td>Non-Energy Benefits</td><td colspan="2">• Less noise
• Reduced maintenance, extends equipment life</td></tr>
<tr><td>Next Steps for Technology</td><td colspan="3">• Analyze cost effectiveness of efficiency gain proposals to BLDC technology
• Support efforts to reduce rare-earth metal use in BLDC motors to reduce costs and improve construction-material availability</td></tr>
</table>

Background

Technology Description

Electric motors drive the compressor and fan(s) in residential HVAC applications. Alternating current induction motors have been the motor of choice in most residential HVAC applications. However, recent decreases in the price of electronic controls have brought old technologies to the forefront of development.

BLDC motors use electric sensors, such as Hall-Effect sensors, integrated inverters, or Electromotive force sensors, to determine rotor position. The sensors allow the BLDC to control the amount of current in the motor, allowing for variable-speed operation.

Switched-Reluctance (SR) motors, a type of BLDC motor, use an electromagnet in the stator and some form of magnetic material formed into salient poles, magnetic poles which have coil windings mounted, for the rotor. SR motors sequentially energizing the stator poles to create rotation. SR requires precise rotor position measurements to determine stator energizing timing, typically performed using the Hall-Effect sensor.

Salient BLDC motors are similar to SR motors; however, the stator and rotor use permanent magnets instead of electromagnets. Similar to a synchronous AC motor, the windings are on the stator, however sensors, such as Hall-Effect sensors, change the pole direction.

According to Ohio Electric Motors (Ohio 2011), BLDC offer a number of advantages compared to standard induction motors, including:

- Lower maintenance and longer life because of no sparking brushes or electrical interference.
- Higher efficiency because of lower friction losses, and variable-speed operation.
- Smaller size and reduced torque-to-weight ratio.
- Higher operating speeds and faster start-up time.

Technical Maturity and Current Developmental Status

BLDC motors are emerging for HVAC applications, and manufacturers are adding BLDC to their HVAC products. Researchers at Tokai University have developed a higher-efficiency brushless DC motor that will be applicable for residential HVAC according to Tetsuo Nozawa at Nikkei Electronics (Nozawa 2009). The BLDC motor reached 96% efficiency by reducing energy losses associated with the control circuit and coil windings. However, the major drawback in the design is higher costs; costs are almost 20 times higher than more commonly used motors.

Barriers to Market Adoption

BLDC motors have higher initial costs than standard induction motors due to additional costs of electronic components. Additionally, Salient BLDC uses rare-earth metals, which have limited supply: most of which is controlled by China.

Energy Efficiency Advantages

BLDC reduces friction and heat losses compared to an induction motor. BLDC uses electronic controls for variable-speed operation, which improves efficiency by allowing part-load operation.

Energy Savings Potential

Potential Market and Replacement Applications

BLDC motors can replace motors in new HVAC equipment in all climate regions in the United States.

Energy Savings

Jim Miller (2010), in an educational blog post for Quantum Devices Inc., notes current BLDC motors are 13-20% more efficiency than a 75% efficiency brushed DC motor.

Tetsuo Nozawa (2009) at Nikkei Electronics notes that Tokai University reached 96% efficiency on a 1/8 horsepower motor.

We estimate HVAC energy savings of 20% based on a CAC/HP with a 90%-efficient BLDC compressor motor and blower motor, compared to 75% efficient induction motors. We based our estimate on the following literature. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.38 Quads of electricity per year.

Cost and Complexity

We estimate a current ¼ hp BLDC motor to cost approximately $50 for a based on the following literature:

- Brushlessdcmotor.net (2012) has a 1/4 hp BLDC motors listed for approximately $50.

Peak-Demand Reduction and Other Non-Energy Benefits

BLDC motors will reduce peak demand through improved motor efficiency and by facilitating variable-speed operation.

BLDC motors benefit from no brushes and create less electromagnetic interference, improving motor life and reducing maintenance. The motors are also quieter than standard AC motors (Ohio 2011).

Next Steps for Technology Development

There is potential to improve the efficiency of BLDC motors even further. Researchers at Tokai University have demonstrated 96% efficiency for BLDC motors with 100W power, which is almost 50% better than minimum DOE standard for a ¼ horsepower small electric motor at 180W. Efficiency gains may not be cost-effective, and analysis could determine viability for of improving BLDC technology. Additional research could examine alternative materials for BLDC construction to alleviate the cost and scarcity of rare-earth metals.

Table G.1.1-2 presents the potential next steps to bring brushless direct-current motors to wider acceptance and achieve significant energy savings in the U.S.

Table G.2-2. Recommended Next Steps for the Development of Brushless Direct-Current Motors

Initiatives	Lead Organization(s)
Analyze cost effectiveness of efficiency gain proposals to BLDC technology	DOE, Manufacturers
Support efforts to reduce rare-earth metal use in BLDC motors to reduce costs and improve construction-material availability	Manufacturers, Industry Organizations

References

Brushless DC Motors. 2012. "GENTEQ Brushless DC Motor, ECM, OPAO, 1/3 HP." Retrieved from http://www.brushlessdcmotors.net/products/type.php?cID=119&tID=289

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Nozawa, Tetsuo. 2009. "[JSAP] Tokai University Unveils 100W DC Motor with 96% Efficiency." TechOn! April 3, 2009

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Sachs et al. 2002. "Residential HVAC Fans and Motors Are Bigger than Refrigerators."Proceedings of the ACEEE 2002 Summer Study on Energy Efficiency in Buildings. 1.261.

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Texas Instruments Europe. 1997 "Digital Signal Processing Solutions for the Switched Reluctance Motor." Texas Instruments Incorporated. Literature No. BPRA058. 1997.

G.3 Smart Refrigerant Distributors

Brief Description	Refrigerant maldistribution in evaporators lowers capacity and efficiency in vapor-compression systems. Smart refrigerant distributors sense and direct the proper amounts of refrigerant to each evaporator circuit, thereby maintaining optimum performance.		
Technical Energy Savings Potential		**Technical Maturity**	**Cost/Complexity**
0.28 Quads/year		Emerging	Medium

Table G.1.2-1 summarizes smart refrigerant distributors for residential HVAC equipment.

Table G.1.2-1. Summary of the Characteristics of Smart Refrigerant Distributors

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Air conditioners and heat pumps	
	Fuel Type	Electricity	
	Technical Maturity	Emerging	
	Most Promising Applications	Unitary equipment	Packaged and split-system configurations.
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency A/C and heat pump equipment	
	Annual Energy Consumption of Baseline Technology	3.06 Quads/yr	
	Applicability to Replacement Market	High	Would be featured in high-efficiency replacement equipment
	Technical Energy Savings Potential	0.28 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Low	Savings would occur primarily off-peak, but varies according to system conditions
	Non-Energy Benefits	• Improved capacity control • Less refrigerant charge • Better heat pump defrost	
Next Steps for Technology	• Conduct third-party, independent laboratory and field testing on HVAC systems equipped with smart refrigerant distributors that use various types of common refrigerants. • Perform real-world testing to quantify the advantage of improved distributor control over the life of the equipment for both heating and cooling applications.		

Background

Technology Description

In a residential vapor-compression air-conditioning system, a two-phase refrigerant enters the evaporator, boiling the refrigerant by extracting heat from indoor air, thereby cooling and dehumidifying the air. Heat pumps operate similarly during the cooling season. The evaporator generally uses multiple refrigerant circuits to reduce pressure drop. Typically, evaporators use distributors (aka, spiders) to divide the refrigerant among the circuits, and employ creative circuiting, intended to ensure that the refrigerant in each circuit boils completely and leaves the evaporator with similar levels of superheat.

Uniform refrigerant distribution and heat transfer is difficult to achieve over a wide range of operating conditions, and refrigerant maldistribution can greatly affect evaporator capacity. Laboratory attempts to mitigate capacity losses by using multiple expansion valves and distributors have experienced limited success. Several factors can contribute to maldistribution, including:

- Impurities in the refrigerant that buildup in evaporator circuits
- Non-uniform airflow through the evaporator (especially important in “A” coils)
- Fouling of the evaporator fins.

Unlike traditional thermostatic expansion valves, smart refrigerant distributors monitor various operating conditions (not just overall superheat) and modulate the amount of refrigerant entering each circuit to maintain the desired superheat. A specialized control algorithm determines evaporator operating conditions through inputs from superheat sensors. The smart refrigerant distributor then meters the desired flow of refrigerant to each individual circuit using digital flow valves, as dictated by the algorithm (see Figure G.1.2-1).

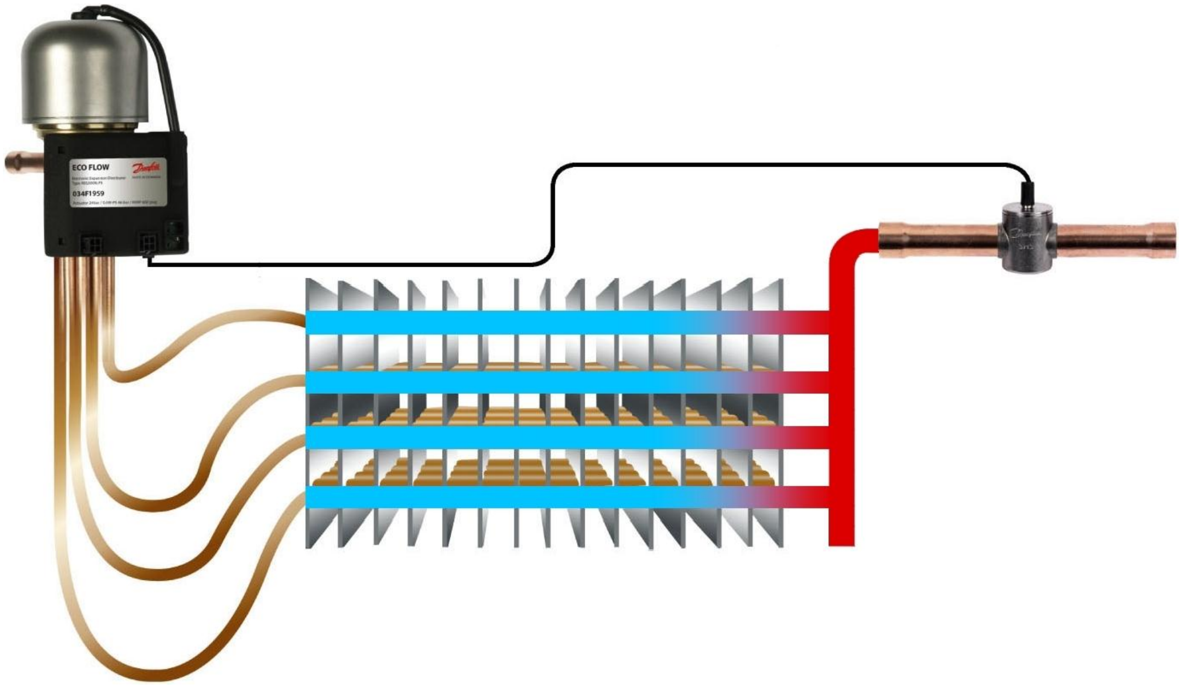

Figure G.3-1. Evaporator with Optimized Refrigerant Distribution

Source: Misfeldt (2010)

Through research conducted at the Technical University of Denmark (DTU), Danfoss A/S has developed an intelligent distributor valve called EcoFlow that they are currently testing for residential applications (1-7 ton capacity). Figure G.1.2-2 depicts the EcoFlow expansion device.

Figure G.3-2. Danfoss EcoFlow Refrigerant Distribution Device

Sources: Tryson (2010) and Danfoss (2009)

EcoFlow utilizes a single superheat sensor placed downstream of the evaporator, continuously measuring the changing evaporator conditions as feedback for its sophisticated control logic. An internal expansion disk powered by a digital motor rotates among the evaporator circuits to precisely distribute refrigerant. The EcoFlow's distribution controls continually adjust the refrigerant flowing to each evaporator circuit through the following strategy:

> "This method of adaptive distribution works as a result of the non-linear behavior of the superheat of the refrigerant, which temperature at the beginning of the dry-zone increases rapidly, and slowly increases towards the air-inlet temperature. Continuous calculations form the basis of a hypothesis about the refrigerant level in each circuit. The EcoFlow tests the hypothesis by adding slightly more refrigerant to one circuit, while reducing the amount to the others. If the superheat measured in the manifold drops, then it is concluded that the dry zone has been reduced and less refrigerant is added to the circuit on the next cycle. On the other hand, if the resulting superheat increases, it is an indication that the circuit that received more refrigerant had a larger dry-zone. The valve will then distribute more refrigerant to this circuit until the superheat reduces. The valve then repeats the action to track changes, and then starts the process again in a continuous cycle." (Danfoss 2009).

Additionally, smart refrigerant distributors provide more efficient heat-pump defrosting by stopping refrigerant flow only in frozen circuits instead of reversing flow in every outdoor circuit. This allows the system to provide heating during the defrost cycle through the rest of the circuits, which can maintain capacity and improve occupant comfort.

Technical Maturity and Current Developmental Status

This is an emerging technology with limited availability in the U.S. market today. Danfoss reports up to a 1.5 SEER improvement for systems equipped with their EcoFlow refrigerant distributor. Purdue University is currently researching the effectiveness of EcoFlow distributors installed on Trane and Carrier cold-climate heat pumps (Groll 2011).

Barriers to Market Adoption

While researchers have studied extensively the effects of refrigerant or air maldistribution across evaporators, techniques to maintain capacity and efficiency are still under development. Because maldistributions are difficult to assess without invasive investigation, it is difficult to quantitatively measure their effect on performance and efficiency. Manufacturers will have to document the improved comfort and energy performance in order for customers to find benefit in smart refrigerant distributors.

Energy Efficiency Advantages

Maldistribution causes a drop in thermal capacity as the system produces less heating or cooling while consuming the same fan and compressor energy. With each circuit receiving the optimum amount of refrigerant, smart refrigerant distributors maintain efficient performance over a wide variety of conditions. By controlling refrigerant flow in frozen circuits, smart refrigerant distributors also can defrost outdoor units more effectively than electric resistance or flow reversal methods.

Energy Savings Potential

Potential Market and Replacement Applications

Smart refrigerant distributors could be used on most residential central air conditioners and heat pumps found throughout the U.S. This technology would be factory-installed on air conditioners and heat pumps for both replacement and new-construction applications.

Energy Savings

Each HVAC system will be affected differently by refrigerant maldistribution, and system energy efficiency gains are difficult to project. The potential benefit of smart refrigerant distributors is directly tied with the amount of maldistribution each system would otherwise experience. Because the effect of maldistribution on capacity is well documented and maldistribution is at least qualitatively known to occur in practice, smart distributors should provide sizable unit energy savings.

Payne and Domanski (2002) tested a variety of evaporators with unregulated maldistributions and found a 30+% drop in capacity without optimized refrigerant distributors.

Kaern and Elmegaard (2009) tested a simplified two-circuit, fin-and-tube evaporator and found an 11-15% drop in capacity due to refrigerant maldistribution. When tested with non-uniform airflow over the evaporator, capacity fell 46-80%. Smart distributors were able to maintain 96% of rated capacity during these events.

Brix (2010) found that a refrigerant maldistribution caused a 20% capacity loss in a laboratory evaporator testing using R-134a and that non-uniform airflow caused a 20-80% capacity loss.

Danfoss (2011) developed a smart refrigerant distributor for residential systems and claims a SEER improvement of 1 point or more resulting from a 15-30% improvement in evaporator efficiency during the cooling season, as well as better defrost control in heat pumps during the heating season.

We chose a unit energy savings of 9% based on the assumption that a smart refrigerant distributor could maintain efficiency 10% better than conventional methods for a 13-SEER split-system air conditioner. We did not include the heating-season energy savings for heat pumps as we have insufficient data to estimate the impacts. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.28 Quads of electricity per year.

Cost and Complexity

This technology would be the successor to advanced expansion valves using modulating stepper motors for more precise refrigerant control. These advanced expansion valves are now found in mid-range products, and not just high-end equipment. While cost information is unavailable at this time, the expected cost premium associated with smart distributors should be minimal.

Peak-Demand Reduction and Other Non-Energy Benefits

Maintaining cooling-system performance lowers electrical demand and improves comfort, but will vary with individual HVAC-system conditions, and would primarily occur off-peak. For heat pumps, smart refrigerant distributors defrost outdoor coils more effectively, maintaining performance in cold weather. Additionally, the controller can enhance FDD capabilities by communicating the status of the evaporator.

Next Steps for Technology Development

Table G.1.2-2 presents potential next steps to bring smart refrigerant distributors to wider acceptance and achieve significant energy savings in the U.S.

Table G.3-2. Recommended Next Steps for the Development of Smart Refrigerant Distributors

Initiatives	Lead Organization(s)
Conduct third-party, independent laboratory and field testing on HVAC systems equipped with smart refrigerant distributors that use various types of common refrigerants.	DOE
Perform real-world testing to quantify the advantage of improved distributor control over the life of the equipment for both heating and cooling applications.	DOE, Manufacturers

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G.4 Alternative Heating and Cooling Technology Options

G.5 Gas-Fired Absorption Heat Pumps

Brief Description	Modern gas-fired furnaces and boilers can achieve efficiencies close to the theoretical limit for combustion appliances (100%). A gas-fired absorption heat pump (GAHP) using a water-ammonia absorption cycle can exceed the thermal output of natural gas combustion to provide space heating at COPs ranging from 1.4-1.7. While a GAHP can be reversible (providing both cooling and heating), the efficiency gain compared to conventional equipment is for the heating mode only.		
Technical Energy Savings Potential		**Technical Maturity**	**Cost/Complexity**
0.66 Quads/year		Emerging	Medium

Table G.2.1-1 summarizes gas-fired absorption heat pumps for residential HVAC equipment.

Table G.2.1-1. Summary of the Characteristics of Gas-Fired Absorption Heat Pumps

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Gas-fired central heating equipment	Also applicable to other forms of central heating, such as oil-fired boilers
	Fuel Type	Gas	Can also be fired using other fossil fuels
	Technical Maturity	Emerging	Commercially available in select U.S. markets for residential use.
	Most Promising Applications	Multi-family and larger single-family residences in cold climates	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Gas-fired equipment over 90% AFUE	
	Annual Energy Consumption of Baseline Technology	1.65 Quads/yr	
	Applicability to Replacement Market	Medium	
	Technical Energy Savings Potential	0.66 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	• Reversible GAHP: summer peak reduction approaches 90% • Heating-Only GAHP: None, if displacing gas combustion heating; approaches 90% (winter only) if replacing electric heat pump	
	Non-Energy Benefits	• Few moving parts in a self-contained system • Non-HFC refrigerant	

Next Steps for Technology	• Develop heating-only GAHPs for wider market introduction by optimizing both cost and energy efficiency for a reasonable payback period. • Conduct long-term field testing in U.S. homes equipped with GAHPs to demonstrate their effectiveness and savings in the U.S. • Promote European GAHP successes throughout the U.S HVAC industry to build up awareness.

Background

Technology Description

Unlike a standard heat pump with an electric compressor, gas-fired absorption heat pumps (GAHPs) utilize the thermal energy of combusted natural gas to drive an absorption cycle. GAHPs can be designed as heating-only or reversible (both heating and cooling) although cooling efficiency (around 0.7 COP) is less than vapor-compression systems. In the heating mode, the absorption cycle transfers heat from both the environment (air, ground, or waste heat) and the combusted natural gas into space heating. While larger absorption systems (predominantly chillers) use a water-lithium bromide solution, GAHPs for residential applications use a water-ammonia solution[14]. An advanced system using a generator-absorber heat exchanger (GAX) harnesses the heat released as the water-ammonia solution absorbs the ammonia gas, increasing the efficiency of the absorption cycle. Figure G.2.1-1 provides a schematic of a heating-only GAHP system. The key steps in the cycle for the heating-mode operation are:

- Ammonia gas evaporates in the outdoor unit (or ground-loop), absorbing heat from the environment, and heads to the absorber
- In the absorber, a water-ammonia solution absorbs the ammonia gas, releasing heat as the solution heads to the generator
- The generator burns natural gas, heating the water-ammonia solution, and releases the ammonia gas from the solution
- The ammonia gas enters the condenser, releasing heat, before traveling through an expansion device, where the gas is cooled, to the evaporator.

[14] The high-pressure ammonia within the sealed system transfers heat sufficiently through a conventional fin-and-tube condenser/evaporator and does not require a separate cooling tower typical for larger LiBr absorption systems.

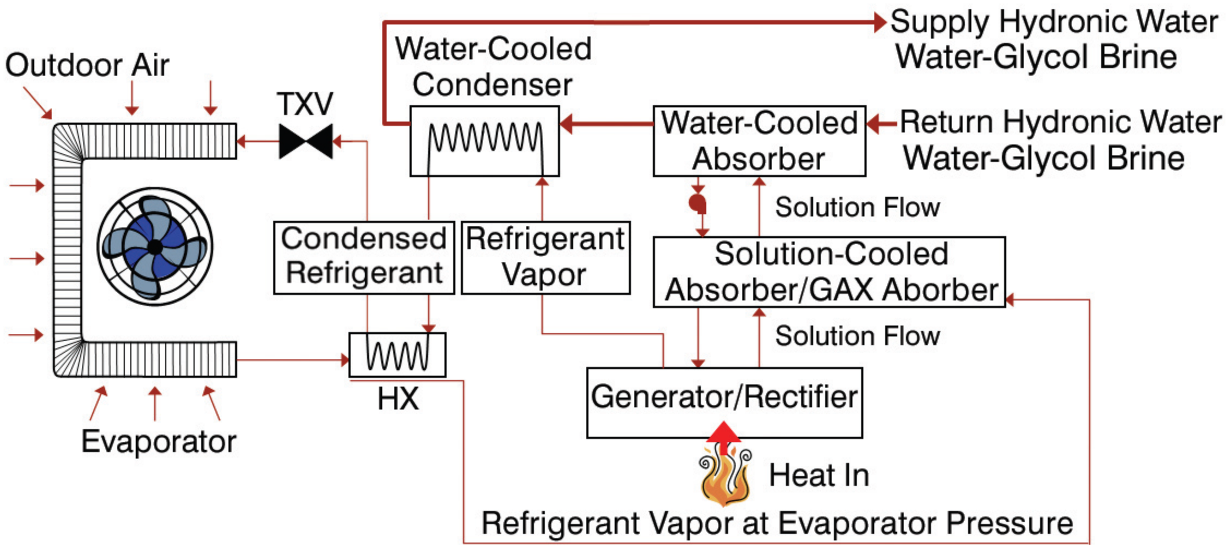

Figure G.5-1. Schematic of a Heating-Only GAHP System employing Generator-Absorber Heat Exchange (GAX)

Source: Dieckmann et al. (2005)

The heat rejected from the absorber and condenser heats a water/brine loop to provide space heating through a hydronic air handler, radiant, or baseboard system. During cold conditions, heat from the combustion of gas can also be used directly as supplemental heating. The system can be configured to withdraw heat from the air, ground loops (acting as a GHP), or waste-heat streams. Integrated into a self-contained unit, the typical design for an air-source GAHP resembles that of an outdoor condensing unit, as seen in Figure G.2.1-2.

Figure G.5-2. Typical Air-Source GAHPs

Source: Robur (2011) and Buderus (2011)

DOE has supported the advancement of absorption HVAC systems for both commercial and residential applications since the 1970s, including:

- From 1981-1996, DOE funded a series of projects with Phillips Engineering to develop a GAX heat pump. Building on the original 1913 design by Altenkirch, Phillips Engineering created a prototype GAX absorption heat pump in 1984-85, with independent testing occurring in 1993. DOE hoped to partner with existing HVAC manufacturers to bring the heat pump to market, but there was little cooperation due to manufacturer concerns that the GAX heat pump would simply displace sales of their current absorption products (DeVault et al. 2005).
- In 1998, DOE supported a joint-venture between gas utilities and manufacturers to commercialize a GAX heating and cooling heat pump under the name Ambian. Although the venture developed a number of prototypes, the incremental costs for the units prevented commercialization (DeVault et al. 2005). In the aftermath of this project, TIAX estimated that a heating-only version of the GAX heat pump could have a cost-reduction of 25-35% (TIAX 2004).
- Under DOE support since the early 2000s, Rocky Research developed, but did not commercialize, a 5-ton reversible GAHP utilizing GAX technology, optimized controls, and other innovations such as specially designed generators, expansion valves, and solution pumps (Rocky Research 2011).
- In the late 1990s, the Italian company Robur worked with DOE and ORNL to develop and commercialize their GAX heat pumps leading to limited introduction into the European market (DeVault et al. 2005). Currently, Robur is the leading GAHP manufacturer in Europe, and has offered products in the Northeast U.S. since the late-2000s.

Technical Maturity and Current Developmental Status

The manufacturers Robur, Buderus, Fulton, Ener-G, FireChill, and Vicot offer GAHPs (both reversible and heating-only) suitable for residential applications, with a number of other manufacturers such Veismann and Vaillant currently developing products. In January 2012, numerous European manufacturers, gas utilities, and other stakeholders kicked off the three-year Heat4U Project to encourage wider adoption of GAHPs[15]. Although this technology is gaining popularity in Europe, acceptance in the U.S. has been slow with only Robur and Fulton having a U.S. presence. Current sales for this technology worldwide are on the order of 5,000 units per year, and have an inherent cost premium from low manufacturing volume. Manufacturers have marketed these systems for high-end customers who would be able to afford the higher upfront cost of the systems with the understanding of significant life-time energy savings.

Barriers to Market Adoption

High first cost is the major barrier for this technology in smaller residential applications, but the economics become more favorable for larger buildings. Most residential customers and HVAC service technicians are unfamiliar with absorption systems. Also, some may be hesitant to use

[15] Funded by the European Commission's Seventh Framework Programme for Research. Details can be found at http://www.heat4u.eu/en/.

ammonia as a refrigerant because of toxicity and flammability concerns. By isolating the refrigerant in the outdoor unit (with all refrigerant connections hermetically sealed at the factory), GAHPs the probability of an ammonia release is greatly reduced. Because the ammonia is outdoors, any leaked ammonia would dissipate quickly into the atmosphere.

Energy Efficiency Advantages

Because the GAHP moves heat from the ambient to the home, they are more efficient than standard gas-fired heating equipment. GAHPs exceed the inherent 100% efficiency limitation of traditional fossil fuel heating systems.

Energy Savings Potential

Potential Market and Replacement Applications

Because of the current price premium, this system is primarily marketed towards multi-family, and larger single-family residences (over 3,000 sq.ft.), especially in colder regions. On a technical basis, this technology would be applicable to all climate regions, and building types.

GAHPs can be installed on new or existing buildings with either a hydronic, forced-air or radiant heating system. The heat pump is self-contained, installed outside the building much like a condensing unit for an air conditioner, with two water/glycol pipes entering the home. Manufacturers offer units in the 100,000-150,000 Btuh range[16], but can be scaled up to meet most thermal loads because of the modular design of GAHPs.

Energy Savings

Although commonly offered in a reversible configuration, this analysis focuses on heating-only equipment because the lower cooling-mode efficiency (0.7 COP) of reversible units does not provide energy savings.

Robur (2009) markets a number of GAHPs with COPs of 1.4-1.7 depending on outdoor ambient conditions and supply-water temperature. This performance is comparable to units offered by other manufacturers.

Dieckmann et al. (2005) stated that GAHPs would have primary energy savings of 40-50% over standard- and high-efficiency gas-fired boilers and furnaces.

Bakker and Sijpheer (2008) tested a GAHP system in a laboratory home in the Netherlands under typical residential loads. They found that the GAHP had 35% energy savings when compared to high-efficiency gas-fired boiler.

Depending on the exact design, the typical electrical consumption for a 120,000-150,000 Btuh system would be on the order of 0.75-1.1 kW, not accounting for the power required for thermal distribution. Ryan (2002) estimates fan and pump electricity consumption at 300 W/ton.

[16] GAHPs are commonly undersized for the building load to minimize cycling losses.

Compared to standard-efficiency central heating equipment using natural gas, we estimate that GAHPs will typically provide a unit energy savings of 40%, including distribution electricity consumption. Individual savings can vary based on climate, system sizing, parasitic energy usage, etc. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.66 Quads of natural gas per year.

Cost and Complexity

GAHPs typically cost 25-300% more than conventional heating equipment depending on capacity, but can have significant energy savings. While reversible GAHPs may eliminate the need for separate air-conditioning equipment and higher electrical service, their cost and complexity increases from the need for multiple reversing valves and greater cooling energy consumption.

Robur (2009) claims a 30-50% annual savings in heating costs with a payback of 2-4 years in climates with high heating loads. When configured with ground loops, installation costs can be 50% less than for a comparable vapor-compression geothermal heat pump because the gas combustion offsets for the heat gain from the ground loops, decreasing the size of the loops.

Dieckmann et al. (2005) estimated that a GAHP optimized for lower cost would have an installed cost premium of $2,000 over a comparable 100,000 Btuh gas furnace at high-volume production. Design trade-offs such as the amount of supplemental heating and reversible operation can affect upfront costs. With less complexity, a heating-only GAHP could cost 25-35% less than a reversible model.

Peak-Demand Reduction and Other Non-Energy Benefits

The working fluids of absorption cycles (e.g., ammonia refrigerant and water absorbent) operate with no ODP, and a low-GWP. These systems operate efficiently down to below freezing temperatures and can modulate their heat output to match thermal demand of the home by controlling the natural gas flow rate. When combined with a storage tank, GAHPs also provide efficient water heating throughout the year and would act as an integrated heat pump (see Section G.3.6).

Next Steps for Technology Development

Further developments to reduce the upfront cost of this technology are the key priority to increasing market adoption. Earlier attempts at commercialization faltered from the high-cost of GAHPs, especially reversible units. Heating-only designs were not seriously pursued because gas utilities supported manufacture development of reversible GAHPs as a way to increase gas usage during the summer months. Although some customers may be interested in a reversible configuration, GAHPs using simpler heating-only designs would have the most reasonable payback and largest national energy savings potential.

Table G.2.1-2 presents the potential next steps to bring gas-fired absorption heat pumps to wider acceptance and achieve significant energy savings in the U.S.

Table G.5-2. Recommended Next Steps for the Development of Gas-Fired Absorption Heat Pumps

Initiatives	Lead Organization(s)
Develop heating-only GAHPs for wider market introduction by optimizing both cost and energy efficiency for a reasonable payback period.	DOE, Manufacturers, Utilities
Conduct long-term field testing in U.S. homes equipped with GAHPs to demonstrate their effectiveness and savings in the U.S.	DOE, Manufacturers, Utilities
Promote European GAHP successes throughout the U.S HVAC industry to build up awareness.	Industry Organizations, Manufacturers

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G.6 Thermoelectric Cooling System

Brief Description	Under an applied voltage, materials known as thermoelectrics generate a temperature difference that can provide residential space conditioning. Although current thermoelectric technology limits its applications to electronics cooling or portable refrigeration, future developments could raise the efficiency and capacity of thermoelectrics to be a non-refrigerant-based replacement for conventional cooling systems.		
Technical Energy Savings Potential		**Technical Maturity**	**Cost/Complexity**
0.58 Quads/year		R&D	High

Table G.2.2-1 summarizes thermoelectric cooling systems for residential HVAC equipment.

Table G.2.2-1. Summary of the Characteristics of Thermoelectric Cooling System

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Vapor-compression cooling systems	
	Fuel Type	Electricity	
	Technical Maturity	R&D	
	Most Promising Applications	Electrically driven air conditioners	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency A/C and heat pump equipment	
	Annual Energy Consumption of Baseline Technology	1.74 Quads/yr	
	Applicability to Replacement Market	Medium	
	Technical Energy Savings Potential	0.58 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	
	Non-Energy Benefits	• No refrigerants • Quiet • High-reliability • Compact	
Next Steps for Technology	• Continue research on high-ZT thermoelectric materials, focusing on materials optimized for cooling applications. • Validate the repeatability and reproducibility of new ZT test methodologies. • Develop the robust fabrication methods to create practical TE systems to test new materials.		

Background

Technology Description

Thermoelectric systems are solid-state systems that convert electrical energy into temperature gradients that drive thermal-energy flows. A thermoelectric element consists of two thermoelectric semiconductors: an n-type conductor (containing negative charge carriers) and a p-type conductor (containing positive charge carriers) placed between two ceramic surfaces, shown in Figure G.2.2-1.

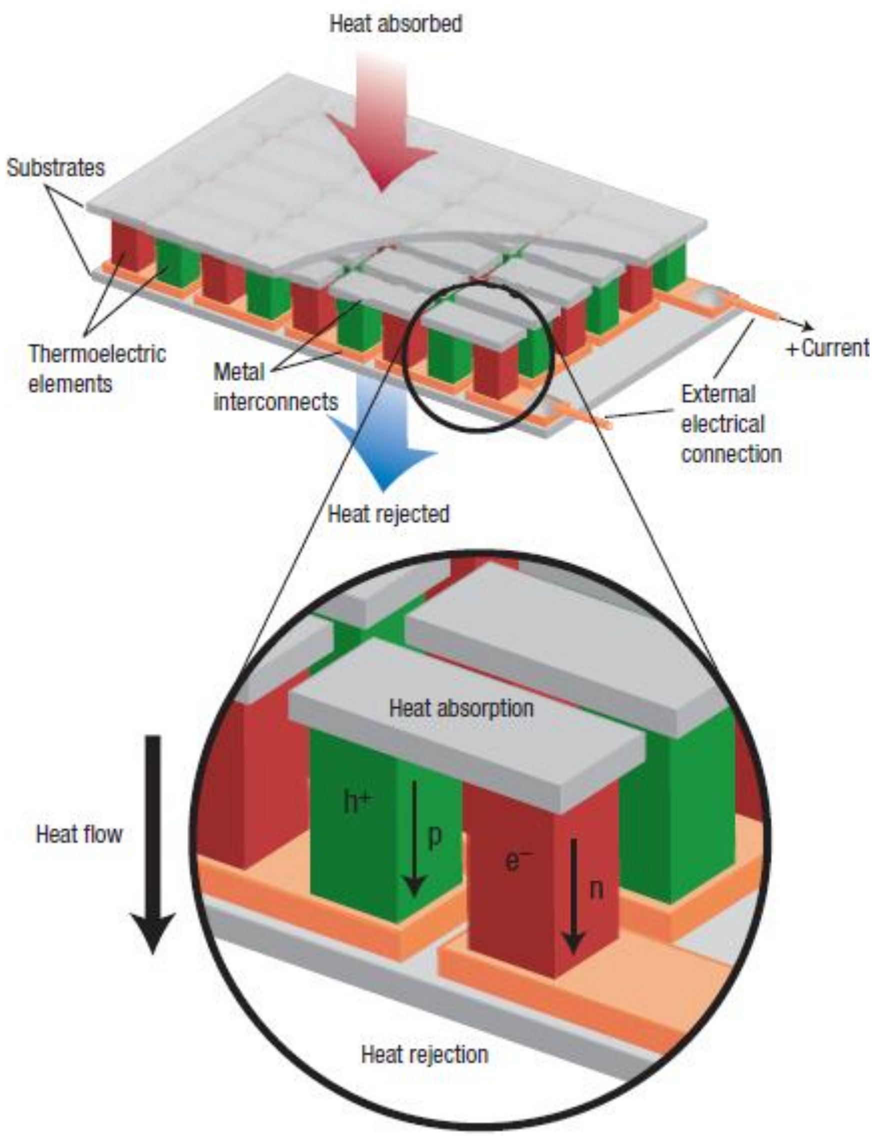

Figure G.6-1. Thermoelectric Cooling Module

Source: Synder and Toberer (2010)

The physical phenomenon that describes both the energy harvesting and thermal conditioning behavior of thermoelectric materials is the Seebeck effect. When placed within thermal gradient, certain materials (thermoelectrics) accumulate charge internally on both the hot and cold surfaces. If the temperature difference is great enough between the hot and cold surfaces, the buildup of charge on the opposite sides of the material creates a voltage difference resulting in a flow of current from the material. Conversely, when voltage is placed across a thermoelectric material, the resulting current moves electrons from one surface to another. This creates a thermal gradient known as the Peltier effect. Although this technology can also supply heating, thermoelectric cooling is of most interest to researchers looking to achieve practical solid-state cooling. Stacking multiple thermoelectric devices in series increases the temperature difference to levels suitable for residential HVAC applications.

Scientists rate thermoelectric materials and Peltier devices by a dimensionless figure-of-merit based on their physical properties and thermal performance. Known as ZT, this measure compares a material’s thermoelectric properties with its thermal conductivity and electrical resistivity in the following relationship:

$$ZT = \frac{\alpha^2 T}{\rho\lambda}$$

Where: α is the Seebeck coefficient (also seen as S), T is the absolute temperature, ρ is the electric resistivity, and λ is the thermal conductivity (also seen as k).

A thermoelectric material’s effectiveness, and therefore its efficiency, is determined by its ZT. Current thermoelectric systems use semiconductor materials with ZT’s around 1.0. Materials produced using quantum dot, thin film, and other nanotechnologies have exhibited ZTs close to 3.0 in laboratory tests (Bell 2009). Figure G.2.2-2 demonstrates some of the measured ZT’s for recently developed materials (as a function of temperature).

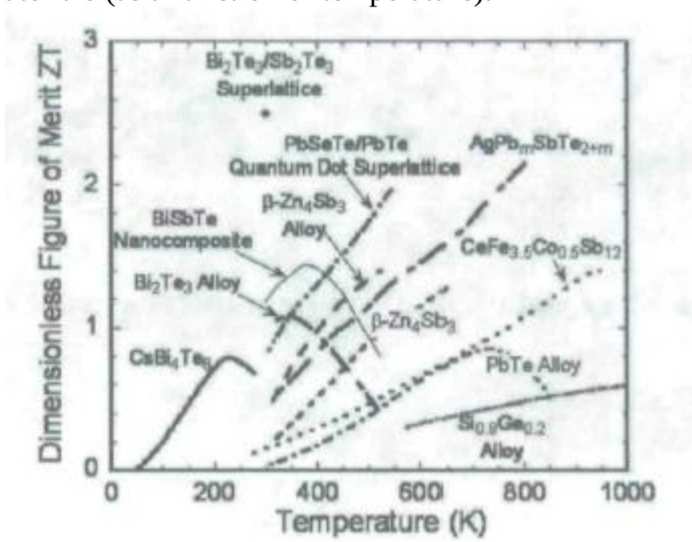

Figure G.6-2. ZT for Various Thermoelectric Materials

Source: Yang et al. (2008).

Technical Maturity and Current Developmental Status

For most residential cooling applications, thermoelectric devices must achieve a ZT of 3 or greater to provide an efficiency advantage. As noted above, some materials have shown this efficiency in a lab environment, but there have been no demonstrations of this performance in a practical HVAC application. Multiple manufacturers have commercialized small, low-efficiency thermoelectric cooling systems as seat conditioning for cars, portable refrigerators, wine cabinets, and spot cooling for electronics. Additionally, researchers have constructed a mechanical subcooler using thermoelectrics to improve efficiency for vapor-compression systems (see Section G.2.3 on thermoelectrically enhanced subcoolers). Thermoelectric generators have also received much attention for their ability to convert waste heat to electricity for automotive and power-plant applications.

Barriers to Market Adoption

The low efficiency of current thermoelectric systems remains the main barrier to broader adoption as an alternative to a vapor-compression cooling plant. Advancement in the material science and fabrication of thermoelectrics are needed to resolve the following issues:

- Ideal thermoelectrics have low thermal conductivity and high electrical conductivity properties, but most materials with high Seebeck coefficients feature both high thermal conductivity and high electrical conductivity.
- Measuring the input variables to ZT is difficult, and most research findings are based on individual variables for one thermoelectric element, and not performance of integrated prototypes. This leads to high uncertainty with test results.
- Small variations in material preparation or fabrication can result in major differences in properties and performance.

Energy Efficiency Advantages

Potential unit energy savings are entirely dependent on the improvements made to material properties. Thermoelectric cooling systems could operate more efficiently than vapor-compression systems when fully developed. Further, it may be practical to make thermoelectric cooling equipment in capacity ranges small enough for individual room conditioning, thereby reducing ducting (or piping) losses and facilitating zone control.

Energy Savings Potential

Potential Market and Replacement Applications

Thermoelectric cooling is an alternative to vapor-compression cooling systems. New and existing homes could use thermoelectrics as the primary cooling plant, or as a supplemental device for localized conditioning.

Energy Savings

For residential HVAC systems, the energy savings of this technology are directly tied to the ZT of the thermoelectric device.

Brown et al. (2010) stated that an HVAC system using currently available thermoelectric materials would have a COP of 1.0-1.5.

Bell, Lon (2008) states that over the last decade researchers have announced materials possessing ZTs between 1.2 and 3.0.

According to Goetzler et al. (2009), researchers claim that fully developed (ZT of 9), high-efficiency thermoelectric cooling systems could surpass the efficiency of conventional cooling cycles by 50%.

For this analysis, we chose a unit energy savings of 33% based on the maximum technical potential for thermoelectrics. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.58 Quads of electricity per year.

Cost and Complexity

According to Dieckmann et al. (2011), thermoelectric systems are currently too expensive to produce for applications above 50W of cooling, regardless of efficiency. Mass production of larger thermoelectric systems presents challenges relating to the specific materials needed. Because maintaining reliable thermal connections is difficult, reliable integration of many smaller thermoelectric units poses additional challenges. These issues add significantly to the current complexity and manufacturing cost of these systems. However, with advances in solid-state manufacturing techniques applicable to multiple industries, thermoelectric cooling systems will likely become easier to integrate into HVAC systems. The inherent simplicity of solid-state cooling technologies placed in the room they're serving can eliminate many of the components in conventional HVAC systems.

Peak-Demand Reduction and Other Non-Energy Benefits

Thermoelectric cooling systems can provide peak-demand reduction in proportion to their efficiency improvements. Thermoelectric cooling systems also have the potential for greater reliability, more compact size, quieter operation, and more modular design (such as using small-capacity units to cool individual rooms). Thermoelectrics do not use refrigerants, so there is no risk of direct release of global-warming gasses during use or disposal.

Next Steps for Technology Development

Although current laboratory research has resulted in ZTs of around 3, materials advancements could lead to much higher efficiencies. Researchers and developers in the thermoelectric industry have compared the advances needed in both thermoelectric efficiency and capacity to the early development of semiconductors and photovoltaics. These technologies can share nanomaterials research and provide a pathway to transform laboratory achievements into commercialized thermoelectric products (Bell 2008).

Table G.2.2-2 presents the potential next steps to bring thermoelectric cooling systems to wider acceptance and achieve significant energy savings in the U.S.

Table G.6-2. Recommended Next Steps for the Development of Thermoelectric Cooling Systems

Initiatives	Lead Organization(s)
Continue research on high-ZT thermoelectric materials, focusing on materials optimized for cooling applications.	DOE, Academic Institutions
Validate the repeatability and reproducibility of new ZT test methodologies.	Industry Organizations
Develop the robust fabrication methods to create practical TE systems to test new materials.	DOE, Manufacturers

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G.7 Thermoelectrically Enhanced Subcoolers

Brief Description	Thermoelectric (TE) devices convert electricity into a thermal gradient that can enhance condensed-liquid subcooling for vapor-compression HVAC systems. While requiring some additional electrical power, TE subcoolers increase evaporator capacity and COP without additional refrigerant flow and the associated compressor power requirement. These subcoolers would be featured in packaged HVAC equipment configured to achieve high efficiency with the added benefit of increased capacity control. Research has shown the effectiveness of this technology in HVAC applications to both raise capacity and COP, but challenges remain to create an efficient, reliable and cost-effective subcooler.		
Technical Energy Savings Potential		**Technical Maturity**	**Cost/Complexity**
0.28 Quads/year		R&D	Medium

Table G.2.3-1 summarizes thermoelectrically enhanced subcoolers for residential HVAC equipment.

Table G.2.3-1. Summary of the Characteristics of Thermoelectrically Enhanced Subcoolers

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Vapor-compression cooling equipment	
	Fuel Type	Electricity	
	Technical Maturity	R&D	
	Most Promising Applications	Split-system air conditioners	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency A/C and heat pump equipment	
	Annual Energy Consumption of Baseline Technology	3.06 Quads/yr	All cooling systems
	Applicability to Replacement Market	Medium	
	Technical Energy Savings Potential	0.28 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	
	Non-Energy Benefits	• Better part-load capacity control • Reduces physical size of equipment • Decreases amount of refrigerant	

Next Steps for Technology	• Continue laboratory research to determine the best orientation of the TE subcooling devices that maximize heat transfer and/or use internal power sources such as a TE generator. • Further advancements in TE technology including improving cost-effective, high-ZT devices • Field testing of various HVAC systems with TE subcoolers to identify optimum configurations and demonstrate reliability

Background

Technology Description

A thermoelectric device (TE) provides cooling through the Peltier effect that occurs when electric current passes through two dissimilar materials connected by a common junction creating both a hot side and a cold side. Typically these materials are n-type and p-type semiconductors with properties that allow for useful solid-state cooling. See Section G.2.2 for more information on the Peltier effect. Figure G.2.3-1 demonstrates the relationship among temperature lift (the difference between the hot/cold surfaces), efficiency (COP), and the power applied to the TE device. As the applied electrical power increases, the temperature lift increases exponentially, although the efficiency of the TE device decreases rapidly. Balancing these three key values determines the effectiveness of adding TE devices to thermal systems. Select applications such as a subcooler enhanced with TE devices could improve COP for vapor-compression HVAC systems.

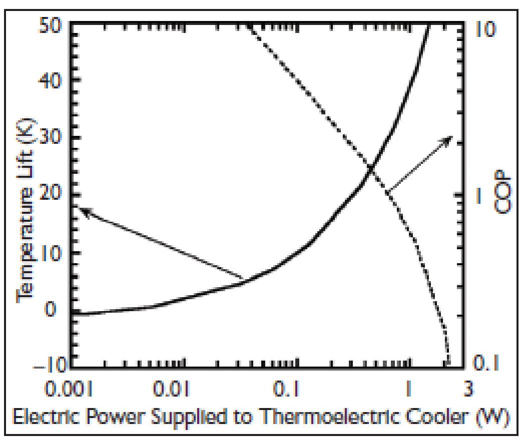

Figure G.7-1. Temperature Lift and COP of a Sample TE Device vs. Applied Power

Source: Radermacher et al. (2007)

Using TE devices for subcooling could benefit HVAC systems more effectively than conventional subcoolers or suction-line heat exchangers. Subcoolers reduce the refrigerant enthalpy entering (and leaving) the expansion device, boosting cooling capacity without additional input from the primary compressor. Ambient subcoolers reject refrigerant heat to the lower temperature of a surrounding medium (usually air), but lose effectiveness during warm conditions. Conventional mechanical subcoolers use smaller, secondary vapor-compression circuits that are too large, complex, and inefficient for low capacity, low lift (~10°F) applications. Suction-line heat exchangers subcool the liquid refrigerant leaving the condenser using the vapor leaving the evaporator, but can increase compressor work. These subcooler variations are more commonly seen in low- and medium-temperature refrigeration systems or as custom solutions for commercial buildings (FEMP 2000).

The cold side of the TE subcooler picks up heat from the refrigerant and expels it (along with the electrical input) through the hot side. Adequate heat rejection from the hot side is necessary to prevent excessive heat buildup in and around the thin TE material, and in turn maintain the effectiveness of the cold side. Active systems use fans and pumps to expel heat from the TE device, while passive systems use natural convection. If placed within the condenser housing, the condenser fan could also provide forced convection to promote heat rejection from the TE device. Figure G.2.3-2 shows a cross-section of a prototype TE subcooler.

The condensed refrigerant passes through a tube heat exchanger connected to the cold side of the TE device by a thermal interface material (TIM). Electricity to the TE device creates the usable thermal gradient to transfer heat and lower the enthalpy of the refrigerant. The hot side of the TE device rejects heat away from the subcooler, continuing the efficient cooling.

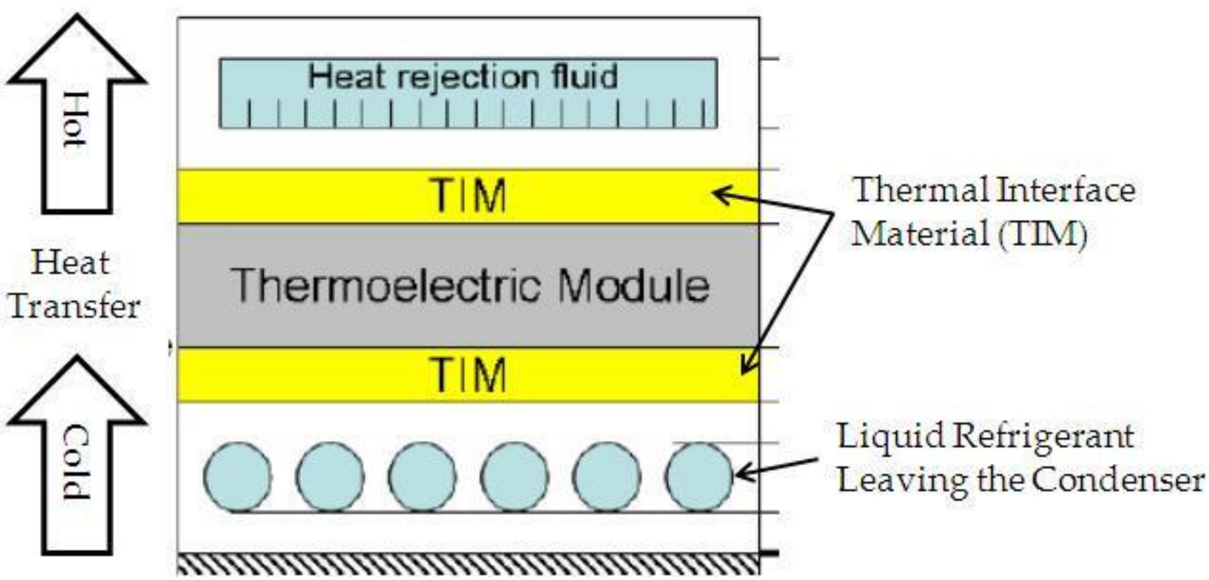

Figure G.7-2. TE Subcooler Cross-Section

Source: Adapted from Schoenfeld (2008)

Current TE devices have a high COP for small temperature lifts and can supplement cooling capacity with less additional energy. When designed correctly, the TE subcooler provides more efficient capacity gains (i.e., the energy consumed by the TE is less than the additional compressor requirement to achieve the same capacity boost). The electricity for the TE can be provided from the HVAC equipment power supply, or a TE generator. The compressor on an HVAC system creates large amounts of waste heat that can be captured by imbedded TE generators[17] (220a) and converted to electricity to power the TE subcooler (220b), as seen in Figure G.2.3-3. The COP of a system featuring a TE-enhanced subcooler would increase even further through the use of a TE generator because there would be little or no external power requirement for the subcooler.

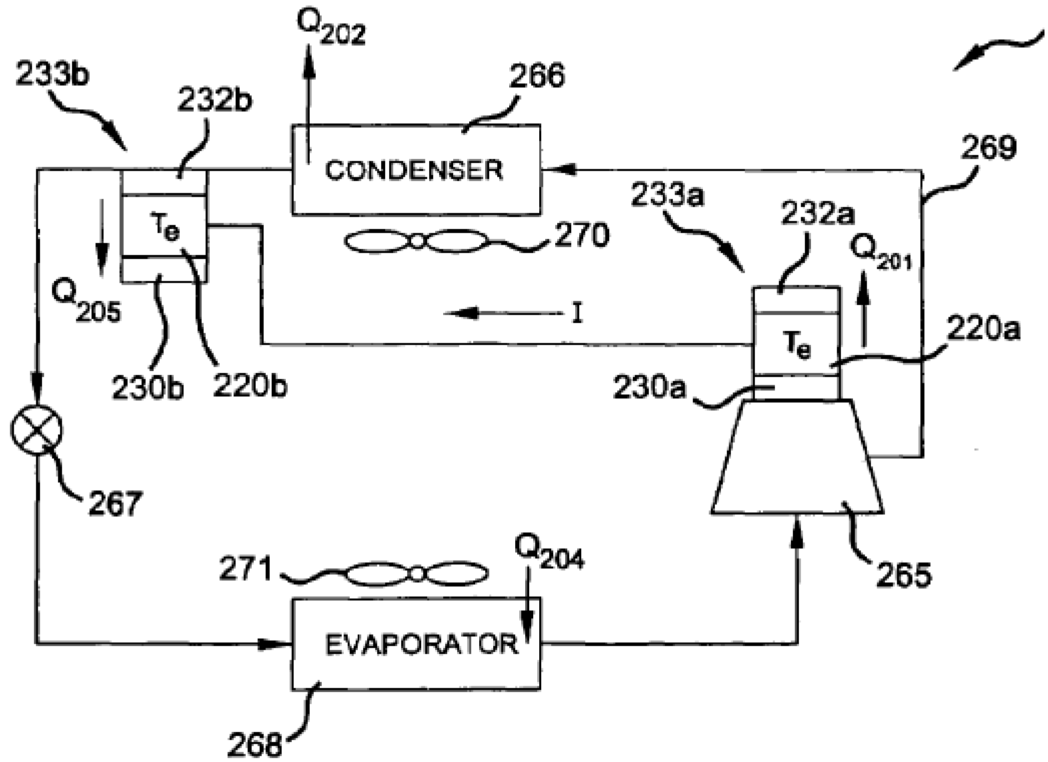

Figure G.7-3. Vapor-Compression System with TE Subcooler Powered by TE Generator

Source: Akei et al. (2007)

Depending on the size and requirements of the air-conditioning system, the TE subcooler could consist of one or many TE subcoolers staged in series as seen in Figure G.2.3-4. Because the efficiency and temperature lift of the TE device varies inversely with the applied electrical power, system controls can optimize the TE subcooler to accomplish different goals. When necessary, the TE device could increase cooling capacity with an additional electricity requirement much less than would be required by the compressor. Because the TE could provide this additional capacity more efficiently, the main compressor could be downsized and operate for longer cycles, reducing losses associated with frequent start-up.

[17] Thermoelectric generators operate in reverse of subcoolers; they convert thermal energy from a temperature gradient into electrical power.

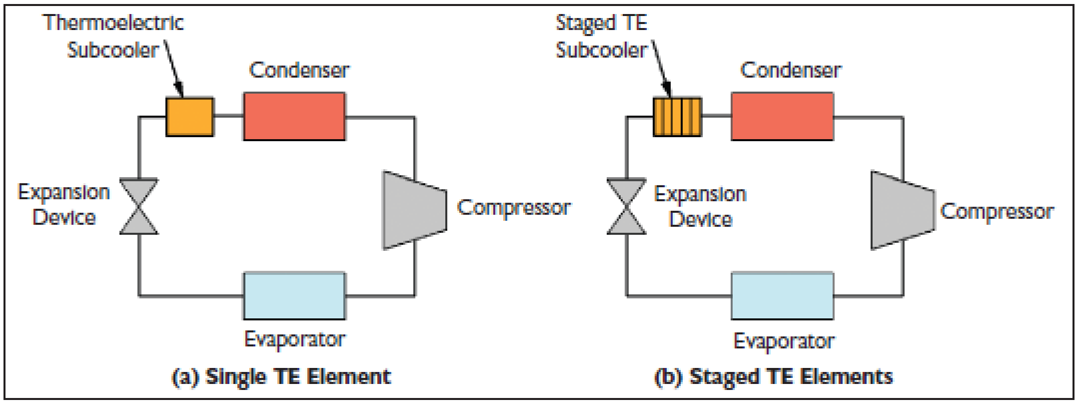

Figure G.7-4. Vapor-Compression Systems with TE Subcoolers

Source: Radermacher et al. (2007)

Technical Maturity and Current Developmental Status

This technology is not commercially available, with a few significant technical issues that require long-term R&D efforts before they are resolved. Researchers at the University of Maryland have developed a number of prototypes and continue their work to create a reliable TE subcooler.

Barriers to Market Adoption

Material and manufacturing limitations pose problems for the use of TE devices in many HVAC applications[18]. High-ZT materials commonly use rare-earth minerals which could present issues relating to material availability, cost, and environmental impacts. Although not practiced widely on residential HVAC systems, other subcooling approaches may be more easily implemented.

Energy Efficiency Advantages

Because of their unique characteristics, TE devices used for refrigerant subcooling provide additional cooling capacity using less energy than would be required by a compressor alone. Although other subcooler technologies exist for refrigeration and commercial applications, TE-enhanced subcooling offers a viable subcooling option with high-controllability for residential systems once fully developed. Although today's readily available TE devices have a ZT (the TE figure-of-merit) around 1, they are sufficient for subcooling applications (Schoenfeld, 2008).

Energy Savings Potential

Potential Market and Replacement Applications

Although retrofit may be possible, TE subcoolers would likely be integrated into new, high-efficiency unitary equipment such as typical outdoor condensing units.

[18] We selected thermoelectric cooling systems as a technology for in-depth analysis and is described in Section G.2.2. The material and manufacturing limitations common for thermoelectric applications are listed in the description.

Energy Savings

Additional capacity from the subcooler reduces the size and energy requirements for the compressor, but may require larger condensers and fan motors. TE-enhanced subcoolers can provide improved capacity control in systems using fixed-speed compressors. Because the COP of TE subcoolers varies with the level of capacity enhancement, the energy savings will vary with different system design goals.

A literature search revealed the following unit energy savings estimates:

- Radermacher et al. (2007) found that TE subcooling would increase system efficiency by 10-30%. They estimated that a system using R-134a could anticipate a 3.5% increase in COP for every 9°F of subcooling.

- Schoenfeld (2008) built and tested a number of TE subcoolers for a carbon dioxide transcritical refrigeration system. By modifying the configuration and applying power to the TE subcoolers, they operated the system for most efficient capacity addition (highest COP) and maximum capacity increase. With the addition of the TE subcooler, maximum COP increased by 10% while overall capacity could increase by 24% with nominal COP change.

We conservatively estimate an average unit energy savings of 9% for vapor-compression cooling equipment based on a fully developed subcooler using high-ZT materials. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.28 Quads of electricity per year.

Cost and Complexity

Because TE subcoolers are in the development stage, little information is available regarding their cost. Radermacher et al. (2007) notes that the additional costs of the TE material, power supply, and manufacturing could be significant. Optimization of the heat exchanger, airflow, and compressor selection would be needed to integrate the TE enhancements. As stated earlier, the capacity increases would reduce the size of other components (e.g., the compressor), somewhat offsetting the cost of the TE subcooler.

Peak-Demand Reduction and Other Non-Energy Benefits

The overall system efficiency improvement provided by TE subcoolers lowers peak demand for air conditioning. Using TE to enhance heat transfer in conventional HVAC systems could reduce the physical size of equipment and amount of refrigerant needed.

Next Steps for Technology Development

Table G.2.3-2 presents the potential next steps to bring thermoelectrically enhanced subcoolers to wider acceptance and achieve significant energy savings in the U.S.

Table G.7-2. Recommended Next Steps for the Development of Thermoelectrically Enhanced Subcoolers

Initiatives	Lead Organization(s)
Continue laboratory research to determine the best orientation of the TE subcooling devices that maximize heat transfer and/or use internal power sources such as a TE generator.	DOE, University Research
Continue research on high-ZT devices achieving a greater COP and lowering manufacturing costs of the TE materials.	DOE, Manufacturers, University Research
Conduct field testing of prototype TE subcoolers in manufactured equipment to determine operational reliability and best practices.	DOE, Manufacturers, Industry Organizations

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G.8 Thermotunneling Cooling System

Brief Description	Thermotunneling cooling system is an advanced form of thermoelectric cooling that transmit electrons across a vacuum to obtain cooling and heating. Although modeling suggests large potential energy savings, this solid-state technology requires additional long-term research to solve a number of technical concerns.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.23 Quads/year	R&D	High

Table G.2.4-1 summarizes thermotunneling cooling systems for residential HVAC equipment.

Table G.2.4-1. Summary of the Characteristics of Thermotunneling Cooling Systems

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Central cooling and heat pump systems	
	Fuel Type	Electricity	
	Technical Maturity	R&D	
	Most Promising Applications	n/a	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency A/C and heat pump equipment	
	Annual Energy Consumption of Baseline Technology	1.74 Quads/yr	
	Applicability to Replacement Market	Medium	
	Technical Energy Savings Potential	0.23 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	Demand reduction associated with improved cooling efficiency.
	Non-Energy Benefits	• Improved reliability • Quiet operation • No refrigerants	
Next Steps for Technology	• Identify and investigate various low-work function materials that could show potential for thermotunneling systems. • Develop the fabrication techniques needed to maintain the precise orientation and conditions for the thermotunneling device. • Develop a prototype thermotunneling device showing a verified cooling effect and investigate its performance over time.		

Background

Technology Description

Like thermoelectrics, thermotunneling is a solid-state cooling technology enabled by the Peltier effect that may be suitable for HVAC applications once fully developed. Thermotunneling is based on the scientific principle that the energy needed to transfer electrons between two surfaces is reduced when the two surfaces are only nanometers apart operating in a vacuum, because of a quantum process called quantum tunneling (or field emission)..

Thermotunneling cooling systems consist of three main elements, as shown in Figure G.2.4-1:

- Under an applied voltage, an electron-emitter plate emits high-energy electrons, cools down as a result, and provides a low-temperature surface.
- An electron-collector plate absorbs high-energy electrons, heats up as a result, and provides a high-temperature surface.
- The proximity of the plates reduces electron migration, and determines the overall effectiveness of the thermotunneling process.
- A thin vacuum layer or evacuated gap lies between the plates and reduces backwards heat transfer, raising system efficiency.

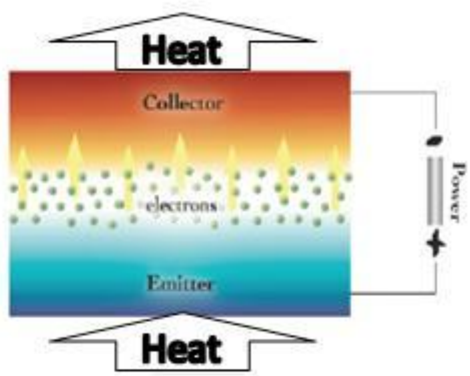

Figure G.8-1. Schematic of Thermotunneling System

Source: Cool Chips PLC (2011)

The system must use low-work function materials on the plate surfaces that have a low energy threshold for electron emission to obtain the advantages of a thermotunneling system. Nano-engineering of the material surface can further enhance their material properties.
The limited understanding of the quantum-mechanical effects involved and the nano-scale surface interactions of the materials, as well as challenges in limiting the losses from thermal radiation, inhibit the development of these systems. The plates of a thermotunneling device require precise orientation to ensure good performance. The plates must be normal to each other, separated by only nanometers, in a vacuum. It will be difficult to hold these tolerances during manufacturing and then maintain them for the life of the product.

Technical Maturity and Current Developmental Status

This technology is not commercially available and presents significant technical issues that require long-term R&D efforts to resolve. Continued research is needed to determine whether thermotunneling cooling could be a viable alternative to conventional vapor-compression technology.

Over the course of a 3-year DOE research project, GE investigated various low-work-function materials and identified a number of designs for thermotunneling cooling systems, but did not produce a prototype with sufficient cooling capacity. Private companies such as Borealis Exploration Limited and Tempronics, Inc. are also investigating applications for thermotunneling technology. Borealis Exploration Limited reports that they have proof-of-concept prototypes and are looking to make commercial prototypes under the licensed name of “Cool Chips” (Cool Chips PLC 2012). Brown et al. noted that, despite having many patents, Borealis Exploration Limited have not developed a prototype (Brown et al. 2010).

Barriers to Market Adoption

Because no laboratory prototype has demonstrated verifiable cooling performance, significant materials and fabrication hurdles remain for thermotunneling cooling. Scientists must achieve efficient performance at practical cooling capacities for thermotunneling systems to enter the product development stage for HVAC applications.

Energy Efficiency Advantages

Thermotunneling cooling systems are a solid-state cooling technology that once fully developed, could operate more efficiently than vapor-compression systems.

Energy Savings Potential

Potential Market and Replacement Applications

Thermotunneling cooling systems are an alternative to vapor-compression cooling and heat-pump systems. New and existing buildings could use thermotunneling in all space heating and cooling applications as either the primary cooling or heating source. Although thermotunneling could be applied for space heating, this analysis focuses on cooling only because it is the subject of most research in this area.

Energy Savings

Weaver et al. (2007) reports that, based on theoretical modeling, thermotunneling cooling systems have the potential to reach a Carnot efficiency of 80%, compared to vapor-compression systems that typically operate at 40-45% of Carnot efficiency. Accounting for ancillary losses in a complete thermotunneling system, they estimated space-cooling efficiency gains of about 35% over conventional vapor-compression technology.

Cool Chips PLC (2011) notes that thermotunneling cooling could achieve 50-55% of Carnot efficiency, resulting in 0-15% efficiency improvement compared to vapor-compression systems after counting for losses.

We chose a unit energy savings of 13% based on the assumption that a fully developed thermotunneling system would increase cooling efficiency by 15%. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.23 Quads of electricity per year.

Cost and Complexity

An estimate for the potential incremental cost for thermotunneling cooling is unavailable given the technological breakthroughs still needed to demonstrate a functional prototype for HVAC applications. Once fully developed, this solid-state technology could eliminate the vapor-compression circuit, and only require fans or pumps to distribute thermal energy.

Peak-Demand Reduction and Other Non-Energy Benefits

Because thermotunneling cooling systems are projected to operate at higher efficiencies than conventional systems, they could provide a commensurate reduction in peak demand. Like other solid-state cooling technologies, thermotunneling cooling systems are silent, can be placed virtually anywhere, and do not use refrigerants. Thermotunneling may have high reliability once fully developed, but ensuring a vacuum at nanometer-sized gap may prove difficult.

Next Steps for Technology Development

Brown et al. (2010) reports some of the advances that must occur for thermotunneling cooling to be viable, including:

- Research and development of designs that establish and maintain nanometer-scale gaps over larger areas, and keeping electrode materials clean during fabrication and assembly
- Development of low-work-function materials for thermotunneling designs
- Development of semiconductor materials for designs using nano-structured superlattices with improved thermal properties
- Development of more precise control of the energy levels of emitted electrons.

Table G.2.4-2 presents the potential next steps to bring thermotunneling cooling systems to wider acceptance and achieve significant energy savings in the U.S.

Table G.8-2. Recommended Next Steps for the Development of Thermotunneling Cooling Systems

Initiatives	Lead Organization(s)
Identify and investigate various low-work-function materials that could show potential for thermotunneling systems.	DOE, Academic Institutions, Manufacturers
Develop the fabrication techniques needed to maintain the precise orientation and conditions for the thermotunneling device.	DOE, Academic Institutions, Manufacturers
Develop a prototype thermotunneling device showing a verified cooling effect and investigate its performance over time.	DOE, Academic Institutions, Manufacturers

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G.9 Advanced Heat Pump Technology Options

G.10 Ductless Multi-Split System

Brief Description	Ductless multi-split (DMS) or variable refrigerant flow systems (VRF) connect multiple indoor units with a single outdoor unit to provide efficient space heating and cooling. DMS minimize distribution losses common to ducted HVAC systems, and offer improved efficiency over electric-resistance heating.		
Technical Energy Savings Potential		**Technical Maturity**	**Cost/Complexity**
0.22 Quads/year		Commercially Available	Medium

Table G.3.1-1 summarizes ductless multi-split systems for residential HVAC equipment.

Table G.3.1-1. Summary of the Characteristics of Ductless Multi-Split Systems

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	All electric cooling and heating systems	
	Fuel Type	Electricity	
	Technical Maturity	Commercially Available	
	Most Promising Applications	• Multi-family buildings with many units • Buildings without central heating or cooling systems • Homes using electric resistance heating	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency HVAC equipment	
	Annual Energy Consumption of Baseline Technology	2.41 Quads/yr	
	Applicability to Replacement Market	High	Especially for buildings without duct systems
	Technical Energy Savings Potential	0.22 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Varies	There may be savings for winter peaking utilities when replacing electric resistance heat.
	Non-Energy Benefits	• Improved zone control • Simultaneous heating and cooling • Low noise	
Next Steps for Technology	• Perform long-term field studies to determine predictable energy savings estimates for various types of homes. • Develop a test procedure that captures the non-steady-state efficiency benefits of DMS systems. • Offer incentive programs to increase DMS heat-pump use in homes using electric-		

	resistance heating.

Background

Technology Description

Used extensively outside of the U.S. for over 25 years, ductless multi-split systems (DMS) are a highly controllable heating and cooling solution that supplies conditioned air directly to the space without ductwork. Like a conventional split system, a DMS uses an indoor unit and outdoor unit, but without the use of air-distribution ducts. While DMS can be cooling-only systems, this discussion focuses on heat-pump units. In cooling mode, the indoor unit acts as an evaporator and the outdoor unit acts as the condenser, with the roles reversed in heating mode. The indoor units can be wall-mounted, placed within ceilings, or located above the ceiling with minimal distribution ductwork. Multiple indoor units can be linked together to a single outdoor unit through a common refrigerant loop, as shown in Figure G.3.1-1.

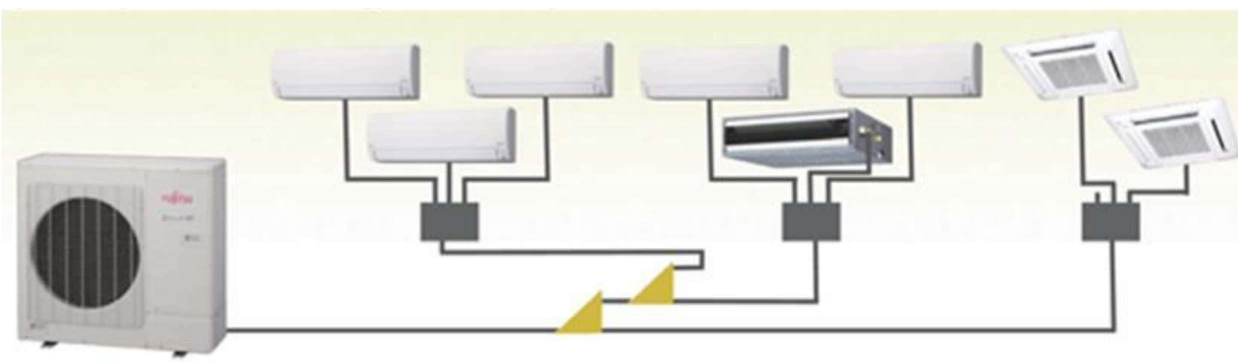

Figure G.10-1. Example Ductless Multi-Split System

Source: Pacific HVAC Air Conditioner (2012)

Manufacturers use various control algorithms to provide thermal comfort efficiently. Each indoor unit contains an electronic liquid-expansion valve to precisely control the supply of refrigerant to match the space-conditioning load. When the room temperature deviates from the setpoint, the control system opens the expansion valve for the indoor unit in that room, lowering the high-side pressure. The compressor controls react to this change in pressure by increasing the compressor speed. The outdoor unit can serve multiple indoor units by either staggering the operations of the indoor units, or because the rooms call for heating/ cooling at different times. The outdoor unit is generally sized at a lower capacity than the aggregate capacity of the indoor units. For example, a 3-ton outdoor unit may serve four1-ton indoor units.

Variations of DMS systems include ductless mini-splits (only 1 indoor unit per outdoor unit), and variable refrigerant flow or volume (VRF/VRV[19]) systems that typically handle larger

[19] Variable refrigerant volume (VRV) is a trademark of Daikin AC, but is often used interchangeably with VRF.

capacities with over 10 indoor units. The VRF units can either be single-setting (no simultaneous heating and cooling) or dual-setting heat-recovery units (can provide simultaneous heating and cooling simultaneously to different zones). Single-setting DMS systems can have a pair of refrigerant lines for each indoor unit, or a shared supply and return (2-line) configuration. Heat-recovery DMS use a 3-line heat-recovery configuration, and are rare for residential applications, even multi-family. Figure G.3.1-2 shows DMS systems using both a) paired lines to each unit and, b) the shared, 2-line configuration.

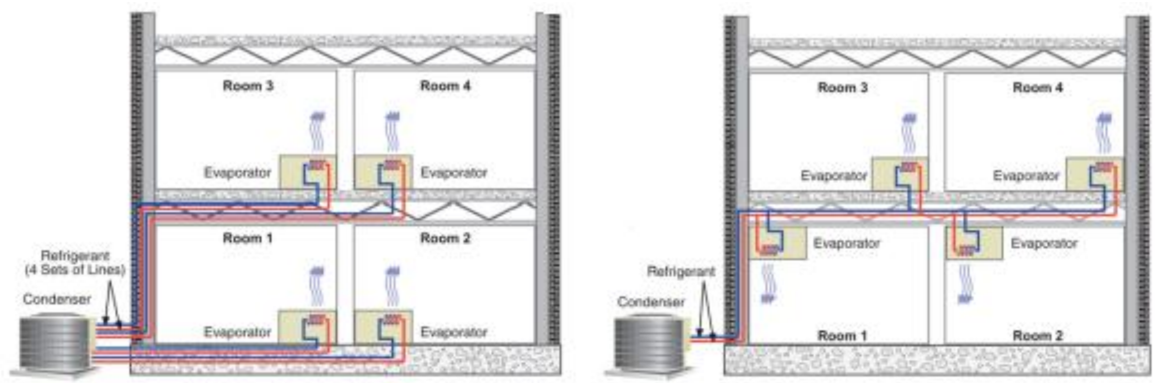

Figure G.10-2. Example Ductless Multi-Split Configurations: 2-sets of lines to each indoor unit, and 2-common lines

Source: Amarnath and Blatt (2008)

Larger VRF systems utilizing heat recovery can supply either heating or cooling to an individual zone by way of a dedicated heating supply line, cooling supply line, and common return line.

Technical Maturity and Current Developmental Status

This is a commercially available technology for both large and small residential buildings. In recent years, overseas manufacturers have either expanded into the U.S. or partnered with domestic manufacturers to market DMS systems to U.S. customers.

Barriers to Market Adoption

Because VRFs do not provide ventilation, a separate ventilation system is needed, potentially adding cost and complexity. Most of the residential building stock currently does not use active ventilation because of fenestration, but with building codes specifying tighter envelopes, this may become an issue for energy-efficient homes. Like all heat-pump systems, a DMS loses heating efficiency as outdoor temperature drops, and may require a backup system. Each indoor unit must have adequate condensate piping to a drain, which may pose an issue for some locations. Because the system requires longer runs of refrigerant lines and additional field joints (two for each indoor unit) compared to conventional split-system units, there is an increased risk of refrigerant leakage.

Energy Efficiency Advantages

For homes using electric baseboard heating, DMS offer an option to incorporate COPs greater than 1 while still using electricity as a heating fuel. Coupled with existing baseboard heaters, DMS can provide efficient heating during moderate conditions and supplement the baseboard heat during cold conditions.

DMS systems reduce building energy use in a number of ways compared to conventional split-system heat pumps and air conditioners. Because DMS are typically located within the conditioned space, reducing both fan and thermal losses associated with leaky ducts outweighs any thermal losses from the insulated refrigerant lines. At part-load conditions, the inverter-driven compressor continually adjusts its speed to match load efficiently, reducing the losses associated with frequent compressor cycling. By providing individual zone control, the system only conditions the areas of the house that need it, which is an improvement over central systems supplying the entire house. For heat-recovery units in multi-family buildings using a central system, waste heating/cooling energy is used to precondition refrigerant flows, reducing compressor usage. All of these features combine for considerably improved part-load performance compared to conventional ducted equipment.

Energy Savings Potential

Potential Market and Replacement Applications

DMS systems are popular retrofit solutions for buildings that do not have central HVAC systems (currently using window, wall, or baseboard units) because they are relatively easy to install and provide higher efficiency than other options. McRae et al. (2010) describes a number of successful utility programs in the Northwest that have added DMS heat pumps to displace the use of electric-resistance heating. For an older home known to have leaky ductwork in a difficult-to-repair location, DMS is an option to decrease energy use.

Energy Savings

The potential market for DMS systems is electric heating and cooling equipment. DMS systems are available with SEER ratings over 20, but efficiency depends on the number of indoor units, as well as the vertical, horizontal and total length of the refrigerant line. The energy savings for DMS systems varies depending on site-specific characteristics, (primarily if there is a duct leakage issue), and the equipment being replaced. In many homes, duct leakage results in a 10-20% loss in system efficiency (Wang et al. 2009).

Goetzler (2007) discussed the advantages of VRF systems in certain commercial building applications. VRF systems can achieve 30% higher efficiency in commercial buildings through improved part-load operation, and through eliminating duct losses. These savings could be representative of the savings for a larger multi-family building using a centralized HVAC system.

Swift and Meyer (2010) described a northeast utility program that installed DMS in homes that used electric-resistance heating. Customers realized a 40% average decrease in their heating electricity usage through the program.

Amarnath and Blatt (2008) surveyed literature on VRF use in commercial buildings. They found a 10-60% HVAC energy savings for commercial buildings using VRF systems. They noted that savings varied with building climate and occupant use.

Because limited information is available on residential DMS, particularly when replacing resistance heat in existing homes, we conservatively estimate an average energy savings of 10% based on information for ducted, commercial systems. Nevertheless, the largest residential energy savings potential lies with replacing electric resistance heating with the higher COP of DMS. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.22 Quads of electricity per year.

Cost and Complexity

Jerome et al. (2011) states that a typical residential DMS installation will cost between $3,000-$5,000, with an additional $1,000 per indoor unit.

NAHB (2008) evaluated the DMS market for the Northwest Energy Efficiency Alliance (NEEA) and estimated an equipment cost of $1,300-$1,500 per ton-cooling capacity with an additional $1,500 for installation. This would place the installed cost of DMS around 30% above conventional equipment.

Goetzler (2007) states that first cost will vary with building application, but a 5-20% cost premium can be expected in commercial buildings. For projects where ductwork or chillers may pose an installation issue, VRF can be cheaper to use. This could be representative for a large, multi-family building.

Karr (2011) estimated the cost of an installed VRF system for a multi-family apartment building to be $14-18/sq.ft.

Peak-Demand Reduction and Other Non-Energy Benefits

The efficiency improvements of DMS occur primarily during off-peak periods, and would have minimal impact on peak demand, unless the DMS replaces electric-resistance heaters for winter-peaking utilities, which are uncommon. DMS systems use specially designed compressors and fans for quiet operation, and there are no ducts to propagate fan and airflow noise. DMS systems provide improved zonal control that enhances comfort. As long as there is reasonable access to an outdoor wall or roof, installation can be relatively easy for retrofit situations.

Next Steps for Technology Development

Because the energy savings of these systems occurs during part-load operations and efficiency is determined by a number of site-specific factors, development of standards and test procedures has been difficult. To encompass the non-steady-state advantages of DMS, AHRI issued Standard 1230 in 2010, which covered the "Performance Rating of Variable Refrigerant Flow (VRF) Multi-Split Air-Conditioning and Heat Pump Equipment," and issued a subsequent certification program in the Fall of 2011 (AHRI 2010).As of this writing, DOE has not approved the standard and still tests DMS systems according to steady-state conditions in accordance with

ARI Standard 210/240-2008. As part of the Building America program, DOE has developed a field-testing methodology to try and validate DMS performance, particularly for systems with multiple indoor units (Christensen et al. 2011).

Table G.3.1-2 presents the potential next steps to bring ductless multi-split systems to wider acceptance and achieve significant energy savings in the U.S.

Table G.10-2. Recommended Next Steps for the Development of Ductless Multi-Split Systems

Initiatives	Lead Organization(s)
Perform long-term field studies to determine predictable energy savings estimates for various types of homes.	DOE, Industry Organizations, Utilities
Develop a test procedure that captures the non-steady-state efficiency benefits of DMS systems.	DOE, Industry Organizations
Offer incentive programs to increase DMS heat-pump use in homes using electric-resistance heating.	DOE, Utilities

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G.11 Gas Engine-Driven Heat Pump

Brief Description	Instead of a utilizing an electrically driven compressor, a gas engine-driven heat pump (GEHP) drives the compressor using the mechanical output of an engine. GEHPs can save energy in two ways: 1) eliminating some of the losses associated with generating and delivering electric energy, and 2) capturing waste heat from the engine and exhaust. Primarily designed for both heating and cooling, GEHPs typically save energy during the heating season, but give up some of those savings during the cooling season.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.15 Quads/year	Emerging	Medium

Table G.3.2-1 presents a summary overview of gas engine-driven heat pumps for residential HVAC equipment.

Table G.3.2-1. Summary of the Characteristics of Gas Engine-Driven Heat Pumps

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Air-source heat pumps	Also gas furnace-A/C combinations
	Fuel Type	Natural Gas and Electricity	
	Technical Maturity	Emerging	Previously introduced for residential systems, but not currently available.
	Most Promising Applications	Regions with large heating or cooling loads	Areas with high electricity rates, or real-time rate structures or other incentives to curtail peak electric demand.
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency air-source heat pumps	Also, high-efficiency gas furnaces over 90% AFUE
	Annual Energy Consumption of Baseline Technology	3.31 Quads/yr	
	Applicability to Replacement Market	Medium	Natural-gas access is generally required for acceptable economics
	Technical Energy Savings Potential	0.15 Quads/yr	Net savings after increased natural gas use from fuel switching
Other Benefits	**Potential for Peak-Demand Reduction**	High	
	Non-Energy Benefits	• Increased comfort associated with capacity modulation • Heat recovery for water heating during cooling mode	

Next Steps for Technology	• Perform field studies in various climate and utility regions to better understand the technical and economic potential of GEHPs. • Develop a standardized methodology to rate the efficiency GEHPs in a way that's comparable to conventional heat pumps, and other HVAC equipment types. • Develop a cost-effective, split-system GEHPs in common residential capacities using engines with minimal maintenance requirements. • Deploy commercialization programs to assist consumer acceptance of the products by offering incentives, technician training, facilitating maintenance contracts, providing advertising and literature, etc.

Background

Technology Description

Direct-expansion (DX) heat-pump systems require compressors to drive the heating/cooling cycle. Unlike most DX systems that use electrically powered compressors, gas engine-driven heat pumps (GEHPs) drive the compressor using an internal-combustion engine. Powered by natural gas, propane, or another hydrocarbon fuel, the engine drives the vapor-compression system without the significant electrical demand of conventional compressors. The compressor connects with the engine's drive shaft, typically with a belt, similar to older automotive air-conditioning systems. GEHPs can supply additional heating capacity by capturing waste heat from the exhaust gases and cylinder jacket. Manufacturers offer GEHPs as packaged or split-system configurations. Figure-G.3.2-1 shows an internal view of the outdoor unit of a split-system GEHP.

Figure-G.11-1. Typical Outdoor Unit of a Split-System GEHP (10-15 Tons)

Source: Sanyo (2011)

Although GEHPs could be designed for heat-only operation (which is where the energy savings accrue), manufacturers have developed equipment offering both heating and cooling capabilities. GEHPs offer a number of operational advantages over standard air-source heat pumps and combination furnace-A/C systems, as summarized in Table G.3.2-2.

Table G.11-2. Comparison of GEHPs to Conventional HVAC Systems

<table>
<tr><th>Comparison Equipment Type</th><th>GEHP Advantages</th><th>GEHP Disadvantages</th></tr>
<tr><td>Standard Air-Source Heat Pumps</td><td>• Heating energy savings, especially with engine heat recovery.
• Controlling the engine speed (rpm) provides effective compressor modulation without the use of power electronics.
• Engine heat recovery improves heating.
• Lowers peak electric demand in both heating and cooling seasons.</td><td rowspan="2">• Higher cooling energy consumption.
• Additional maintenance requirements.
• Increased weight, size, and noise</td></tr>
<tr><td>Combination Furnace-A/C System</td><td>• Heating efficiency over unity using hydrocarbon fuels.
• Lowers peak electric demand in cooling season.</td></tr>
</table>

Technical Maturity and Current Developmental Status

This is an emerging technology for residential applications with limited availability in the U.S. market today. Originally developed in the 1980s, this technology was commercialized in the U.S. for the 3-ton residential market by York (Triathlon) and for larger multi-family buildings by Goetll and others. Because of the high-upfront cost of these systems, issues with engine reliability, and difficulty with the sales and service distribution network, many manufacturers left the marketplace (Ryan 2007). Currently, there are no GEHPs offered in a packaged or split-system configuration commonly seen in residential A/C and heat pump systems.

GEHPs have been more popular in Japan with around 40,000 units sold each year for residential and commercial applications, mostly through partnerships with gas utility companies. Because most Japanese GEHPs are multi-split systems, Japanese manufacturers had little interest entering the U.S. commercial market, which is dominated by packaged rooftop systems. This trend has shifted as multi-splits gain acceptance for commercial and multi-family buildings, causing Japanese manufacturers to either partner or sell products in the U.S. For example, IntelliChoice Energy offers both multi-split and packaged GEHP systems in a partnership with the Japanese manufacturer Aisin.

Barriers to Market Adoption

Currently, high first cost is the primary barrier for residential systems, although GEHPs can be cost competitive for multi-family buildings. The engine increases maintenance requirements compared to conventional electric heat pumps, including spark-plug and oil replacement. Most residential HVAC technicians are not accustomed to providing engine service. Noise and engine emissions, especially carbon monoxide, could be a significant issue. Lastly, the economics for GEHPs will vary depending on the relationship between natural gas and electric rates (and rate structures), making it difficult to project economic return.

Energy Efficiency Advantages

Like most electric-to-gas fuel-switching technologies, GEHPs derive a portion of their energy savings by avoiding some of the losses inherent in the electrical grid. In particular, displacing the generation/transmission/distribution of electricity with the engine drive avoids the losses associated with:

- Transmission and distribution of electricity from the power plant to the home
- Converting shaft power to electricity at the power plant
- Converting electricity to shaft power (using an electric motor).

Most GEHPs require some grid-supplied electricity to power auxiliaries, so these losses are not completely avoided. Also, the engine used in a GEHP is generally less efficient than the electric power plant in converting fuel energy to shaft energy, which generally more than offsets these savings during the cooling season. During the heating season, waste-heat recovery from the engine and engine exhaust bring the GEHP back to a net energy saver on a year-round basis for most climates.

Energy Savings Potential

Potential Market and Replacement Applications

This technology offers primary energy savings for regions with high heating loads. Although current U.S. offerings are for larger building loads (6-tons and up), GEHPs sized for residential loads are available in other countries, and have been previously available in the U.S. GEHPs are suitable for retrofits as long as there is access to a fuel source such as natural gas or on-site propane tank. For single-family residences, the engine would be housed in the outdoor unit of a split system.

Energy Savings

It is difficult to assess the energy savings potential of GEHPs based on the amount of recent available information, particularly for lower-capacity systems suitable for residential applications. The overall primary energy consumption of a GEHP consists of the site-to-source energy conversion, the mechanical and thermal efficiency of the engine, the COP of the vapor-compression system, and the associated electrical parasitic loads such as fans.

GEHPs derive some of their energy savings by eliminating some of the losses associated with the generation and distribution of electrical energy. When accounting for generating losses from central power plants, and delivery losses (transmission and distribution), electricity site-to-source energy ratios[20] are 1 to 3.34. This compares 1 to 1.047 for natural-gas transmission and distribution (Energy Star 2011)[21]. So a building using electricity has a fuel efficiency around 30%, whereas natural gas would be 96% initially, before the fuel reaches the HVAC system.

[20] The site-to-source energy ratio compares the energy consumed upstream of the building to the usable energy content of the fuel. This encompasses losses from generation, transmission, and distribution, but does not cover losses during extraction of primary fuel.

[21] These ratios represent national averages and can vary with the regional generating portfolio or distributed generation on site.

Current DOE standards for a 10-ton electrically driven heat pump specify 11 EER (3.22 COP), so, once accounting for the site-to-source conversion, the primary-energy efficiency becomes:

$$\eta_{Primary} = \frac{3.22\ Btuh\ thermal\ output}{(1\ Btuh \times 3.34) electrical\ input} = 0.96$$

Hepbasli et al. (2009) examined various GEHP designs and stated that the engine efficiency of a typical GEHP is 30-45% with the ability to recover 80% of available waste heat when in the heating mode. Because this report studied GEHPs of varying capacities, this range of engine efficiencies may overstate efficiencies for smaller engines that would be used in residential systems. An analysis[22] of the Honda engine used in freewatt mCHP system revealed a mechanical efficiency of approximately 25% (ECR 2008). This estimate would be more representative for residential GEHP systems.

The site efficiency of the GEHP is determined by the efficiency of the engine and the vapor-compression system, and is commonly expressed as eCOP. Zaltash et al. (2008) tested a 10-ton GEHP rooftop unit that produced a heating eCOP of 1.22 and cooling eCOP of 1.11 at 47 ˚F and 95 ˚F ambient test conditions. Taking into account the site-to-source energy ratios, the primary energy efficiency of these results are:

For heating (before heat recovery):

$$\eta_{Primary} = \frac{131{,}527\ Btuh\ thermal\ output}{(101{,}391\ Btuh \times 1.047)\ natural\ gas\ input + (6{,}142 \times 3.34) electricity\ input} = 1.04$$

For cooling:

$$\eta_{Primary} = \frac{129{,}617\ Btuh\ thermal\ output}{(110{,}295\ Btuh \times 1.047)\ natural\ gas\ input + (6{,}142 \times 3.34) electricity\ input} = 0.95$$

Assuming waste heat recovery of 80% during the heating season, the heating primary energy efficiency becomes:

$$\eta_{Primary} = \frac{131{,}527\ Btuh\ thermal\ output + (69{,}996\ Btuh\ waste\ heat \times 80\%)}{(101{,}391\ Btuh \times 1.047)\ natural\ gas\ input + (6{,}142 \times 3.34) electricity\ input} = 1.48\ .$$

Table G.3.2-3 summarizes the results of this efficiency comparison, and adds a comparison to furnaces. The primary energy efficiency of GEHPs for cooling is slightly lower than for the electric heat pump. Despite increased energy consumption, GEHP cooling that offers lower peak demand and potential operating cost savings would be attractive for certain customers. The primary benefit of GEHPs lies with energy savings for heating.

[22] Engine input of 18,500 Btuh delivers an electrical output of 4,095 Btuh. Estimating electromechanical conversion efficiency from the generator, inverter and other components at 80-90% provides a mechanical engine efficiency of approximately 25%.

Table G.11-3. Comparison of Primary Heating Efficiencies for Various Equipment Types

Equipment Type	Primary Energy Efficiency	Energy Savings of GEHP (%)
GEHP w/ Heat Recovery	1.48	-
Electric Air-Source Heat Pump	0.96	34%
High-Efficiency Furnace (92% Efficiency)[23]	0.88	38%

GEHPs also offer more efficient operation during cold-weather conditions. As ambient temperatures drop, conventional heat pumps lose efficiency by switching to resistance heating. GEHPs maintain capacity, at least partly[24], through combustion of natural gas, providing additional primary energy savings during low-temperature operations.

We chose a unit energy savings of 20% based on the assumptions that a typical residential GEHP application, with a yearly primary energy consumption consisting of a 60% heating to 40% cooling split[25], would experience a 38% heating savings and a 5% increase in cooling consumption. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.25 Quads of natural gas and 0.41 Quads of electricity per year. Switching every applicable, electrically driven HVAC system to a GEHP would increase natural gas consumption by 0.51 Quads per year for a net savings of 0.15 Quads.

Cost and Complexity

Historically, these systems have a significant upfront premium over conventional systems although specific pricing information is limited. Cost savings and payback for this technology vary based on the price of electricity (consumption and demand) and natural gas in a specific area. A literature search produced the following estimates:

- CDH Energy (1996) estimated the incremental cost of a 3-ton York Triathlon GEHP to be $2,800 above conventional equipment. They noted that this cost was in the first year of production at 2,000 units per year.
- Sohn et al. (2009) installed and monitored a number of 10-ton GEHPs at various military facilities in the Southwest over the course of a year. One site achieved cost savings[26] of 25% over a high-efficiency conventional heat pump under the following utility rates: $0.15/kWh average, $9.54/kW, and $1.31/therm.

[23] For a 92% efficiency gas furnace, the primary energy efficiency would be 0.88.
[24] Depending on the specific GEHP design and sizing, some electric resistance heat may be required.
[25] Nationwide average of residential primary energy consumption by end-use taken from 2010 Building Energy Databook. Parts of the Northeast and Midwest have a heating breakdown of 70% and greater, and would have higher energy savings with GEHPs.
[26] Researchers normalized the data in this study for weather, and other consideration.

The size and weight of GEHPs can be problematic for residential installations because of the heavy engine and engine-mounting/skid system. When placed in the yard of a single-family home, specialized sound-proofing or exhaust venting may be necessary.

Peak-Demand Reduction and Other Non-Energy Benefits

By eliminating the largest electricity draw of a heat pump, i.e., the compressor motor, GEHPs greatly reduce peak demand, particularly during the cooling season. Changing the speed of the engine provides effective capacity modulation, which facilitates maintaining more uniform indoor temperatures for increased comfort. During cooling mode, waste heat from the GEHP could be diverted for domestic water heating, increasing energy efficiency, but with added complexity.

Next Steps for Technology Development

While GEHPs have achieved market success for multi-family buildings in Japan, much is needed to increase adoption of this technology in the residential U.S. market. The first introduction of GEHPs to the U.S. through the York Triathlon was unsuccessful for a number of reasons, including:

- The purchase price was significantly higher than conventional equipment.
- Units were only offered at a single 3-ton capacity, and the target market of higher-income homes typically requires a larger unit.
- The distribution and service network was not well established and customers were unfamiliar with the equipment.
- Installation costs were higher than conventional units due to the larger size and weight of the units as well as contractor inexperience with the additional glycol loop of the 4-pipe configuration.
- Despite its promising performance, the relatively stable natural gas and electricity rates in many markets during the 1990s and early 2000s resulted in excessively long payback periods.

Opening the market to single-family homes will require a quiet, reliable unit offered in a range of capacities that can easily retrofit into existing ductwork with a reasonable payback. Modular multi-split systems are suitable for apartment buildings, but to reach single-family homes, GEHPs should be configured as packaged or split systems.

Table G.3.2-4 presents the potential next steps to bring gas engine-driven heat pumps to wider acceptance and achieve significant energy savings in the U.S.

Table G.11-4. Recommended Next Steps for the Development of Gas Engine-Driven Heat Pumps

Initiatives	Lead Organization(s)
Perform field studies in various climate and utility regions to better understand the technical and economic potential of GEHPs.	DOE, Manufacturers, Utilities
Develop a standardized methodology to rate the efficiency GEHPs in a way that's comparable to conventional heat pumps, and other HVAC equipment types.	DOE, Industry Organizations
Develop cost-effective, split-system GEHPs in common residential capacities using engines with minimal maintenance requirements.	DOE, Industry Organizations, Manufacturers
Employ commercialization programs to assist consumer acceptance of the products by offering incentives, technician training, facilitating maintenance contracts, providing advertising and literature, etc.	Utilities, Manufacturers

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G.12 Geothermal Heat Pump

Brief Description	Geothermal heat pumps utilize alternative thermal sources/sinks to operate a vapor-compression heat pump more efficiently. Although these systems have been installed in the U.S. for decades, GHPs using high-efficiency components, alternative loop designs, advanced drilling techniques, and better field measurement strategies could lower the upfront cost of these systems and increase their market adoption.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.48 Quads/year	Emerging	High

Table G.3.3-1 summarizes geothermal heat pumps for residential HVAC equipment.

Table G.3.3-1. Summary of the Characteristics of Geothermal Heat Pumps

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Central HVAC equipment	Air-source heat pumps and gas furnaces/air conditioners
	Fuel Type	Gas and Electricity	
	Technical Maturity	Emerging	
	Most Promising Applications	New construction, particularly housing developments, or multi-family buildings	Often retrofit as well for homes with existing duct systems.
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency central HVAC equipment	
	Annual Energy Consumption of Baseline Technology	1.59 Quads/yr	
	Applicability to Replacement Market	Low to Medium	25% based on the site-specific issues of this technology.
	Technical Energy Savings Potential	0.48 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	Can be very high in some installations.
	Non-Energy Benefits	• Improved comfort • Reduced noise • Factory-sealed heat pump	
Next Steps for Technology	• Develop a low-cost, reliable method to obtain ground thermal-conductivity measurements to more accurately size ground loops. • Conduct long-term monitoring of GHP installations with different outdoor heat exchanger designs to better understand the effects of ground-temperature fluctuations on efficiency over time.		

	• Develop a validation process where new technologies and methodologies would be investigated, tested, and compared to ensure system performance for both installers and customers. • Investigate alternative ground-coupling techniques, heat sources/sinks, and other high-efficiency technologies to compare their cost and heat-transfer characteristics with current designs. • Develop integrated design and simulation software to consistently size systems appropriately, and provide reasonable estimates on life cycle costs. • Publish best practices for system design, installation techniques, continued performance to increase understanding throughout the HVAC industry and raise awareness of new technologies.

Background

Technology Description

By utilizing the relatively stable temperatures below the Earth's surface as a thermal source and sink, geothermal heat pumps (GHPs) achieve smaller temperature lifts compared to air-source heat pumps and, hence, higher efficiency. Generically, GHP[27] systems consist of an underground thermal source/sink, a reversible heat pump installed indoors, and a distribution system that conditions the living space. When a GHP is designed correctly, the underground thermal mass remains at a relatively constant, moderate temperature year-round (typically 55 ˚F, but varies by region) that raises the heat pump efficiency during both heating and cooling seasons. In heating mode, the ground remains at a higher temperature than the ambient air and is a more effective heat source. Conversely, when the outdoor temperature rises in the summer, the ground is a more effective heat sink than air. Because of this year-round advantage over other technologies, GHPs have been used around the world for decades to provide high-efficiency space conditioning.

The design of GHPs depends on the specific needs of the building, and the available thermal resources. The indoor components of GHPs can accommodate a forced-air or hydronic distribution system, depending on particular building, but maintain the same basic design. The differentiating features of the various GHP designs transfer heat through various mechanisms and strategies, as seen in Figure G.3.3-1. Some of the common GHP variations include:

Closed-Loop – Also known as ground-coupled heat pumps, these systems have a liquid-to-liquid heat exchanger that transfers heat between the indoor refrigerant, and a closed, water or water-glycol loop made from high-density polyethylene. Traditionally the most common GHP configuration, the sealed outdoor loop can be oriented in various ways. Vertical boreholes drilled 150-300 ft. deep can contain U-shaped or concentrically designed loops. Horizontal trenches 4-6 ft. deep can contain either coiled or straight tubing. These systems add significant cost for excavation or drilling compared to other GHP variations, but can be installed in many more locations.

Open-Loop – Water from a groundwater aquifer or concrete storage wells circulates through the liquid-to-liquid heat exchanger, transferring heat with the indoor refrigerant before depositing back into the original source in an open process. While usually less expensive than closed-loop

[27] GHPs are also known as ground-source heat pumps, geoexchange systems, and other names.

systems, local regulations and the aquifer depth restrict the use of this system design in many regions.

Surface-Water – While not technically underground, the lower depths of lakes, ponds, and streams maintain a similarly stable temperature suitable for a heat-pump source/sink. Usually in these configurations, the same closed-loop coils as used in horizontal trenches are submerged to the bottom of the water source. This method can be very economical, if the available resource exists.

Direct-Exchange – Although operating as a closed-loop, this configuration does not use an additional heat exchanger, but rather circulates the refrigerant directly through underground copper or aluminum tubing. Because of this, the system performs without the water circulation pump and additional heat exchanger, reducing upfront and operational costs. Direct-exchange systems may pose the risk of underground refrigerant leaks or insufficient oil return to the compressor. They also require field charging. Direct-exchange systems are relatively uncommon.

Hybrid – This configuration offsets the need for additional ground loops, especially for unbalanced climates[28], by adding an additional heat source/sink such as a cooling tower, condenser or boiler. Section G.3.5 describes Hybrid GHP systems in further detail.

[28]Regions with unbalanced climates have significantly larger heating loads than cooling loads, and vice versa.

Figure G.12-1. Various GHP Designs

Source: Li (2010)

Despite their availability for many years, GHPs have not achieved widespread use in residential HVAC because of space constraints and the added cost of using ground-loops or unconventional thermal source/sinks. Also, because a GHP project requires consideration of the site-specific geological resources in addition to the building loads, these systems typically entail significantly more upfront engineering design and installation complexity than conventional equipment, adding substantially to installed costs. Although GHPs can last longer than conventional equipment[29] (lower temperature lifts place less stress on equipment) with higher energy savings, this results in a markedly higher upfront cost that deters many homeowners from these systems.

[29] Conventional HVAC equipment has a lifetime between 10-15 years. The heat pump for a ground-coupled system has a lifetime of 20-25 years or greater. The ground-loops themselves have a lifetime of 50 years or greater.

Because GHPs have proven their energy-efficient performance in hundreds of thousands of U.S. installations, the major hurdle to their increased adoption stems from their long payback period. In many cases, the incremental cost premiums over high-efficiency air-source heat pumps or gas furnace/air conditioner combinations are not affordable to many homeowners. Even after government or utility incentives, GHPs can have payback periods over 10 years in many parts of the country because of the higher upfront costs-particularly those associated with the excavation and drilling for the ground loops.
A number of emerging technologies and strategies hope to reduce the payback period for GHPs by both increasing system efficiency and lowering the project costs including:

- **High-Efficiency Components**
  Borrowing specific technologies developed for other HVAC equipment types, GHPs can utilize variable-speed compressor, pump, and fan motors to raise the efficiency of the heat pump and indoor distribution system. Circulation pumps can account for over 30% of total GHP energy consumption, and using variable-speed controls can decrease this associated pump consumption by 60-80% (Klaassen 2009). For larger multi-family buildings, Mitsubishi and Daikin can configure their ductless multi-split systems to use ground loops instead of an air-side heat exchanger for greater efficiency. Additionally, an integrated heat pump that provides both space conditioning and on-demand water heating can be configured with a ground-loop heat exchanger (see Section G.3.6).

- **Advanced Drilling Techniques**
  While this drilling well disturbs only a small amount of land during installation, closed-loop vertical borehole systems have significant costs related to the drilling process. While the time and cost for conventional auger or air/mud rotary drilling has decreased as GHPs have become more prevalent, new drilling technologies could speed the process further:

  - Sonic Drill Corp. has commercialized equipment that provides sonic vibrations to the drill bit, reducing drilling time by over 60%. This technique replaces drilling mud with water slurry, which minimizes site cleanup after drilling.

  - Potter Drilling Inc. has developed a thermal spallation drilling technique that applies high heat to the rock surface, cracking imperfections between mineral grains. This results in faster drilling in difficult locations. While this technology was initially conceived for drilling wells for geothermal power plants, it could find applications for GHPs in rocky locations.

- **Alternative Ground-Loop Designs**
  The orientation and depth of the underground loops also influences the installation costs of GHPs, and can be improved by limiting the number and depth of the underground loops.
  - For borehole systems, directional drilling technology allows many individual loops to be drilled on an angle from a central ground penetration. While the underground loops may cover more land than a vertical borehole configuration, loops can be placed under inaccessible land, and avoid underground obstacles.

- Foundation heat exchangers can be incorporated around the basement and foundation of new houses, where the ground is already exposed. This minimizes the additional excavation or drilling needed for GHP loops.

- GeoEnergy Enterprises has developed a pre-fabricated well for direct-exchange systems that immerses a copper coil into a water-filled cistern. The self-contained system installs to only a 23 ft. depth, reducing drilling time, and utilizes the water as a buffer to ground temperature fluctuations, improving performance.

- **Simulation and Field Measurements**
  Because the outdoor heat exchanger is the largest single cost for the system, optimizing the depth, size, and number of ground loops is imperative to the competitiveness of GHPs. System designers rely on simulations to determine site-specific requirements. The lack of site-specific data (traditionally drawn from regional geological surveys) often leads to oversizing, and increased system cost. Researchers at Oklahoma State University have devised a field-measurement system that provides a known heat flux through a borehole loop for 2-3 days to measure the underground thermal properties (Austin et al. 2000). Although this measurement system is applicable to most vertical-borehole GHP projects, the current cost of $6,000-$8,000 per site limits its use primarily to commercial applications (Klaassen 2009). Handheld conductivity probes exist but may not provide an accurate representation of the soil conditions for the proposed site (Hughes and Im 2012). Developing a cost-effective field-measurement tool for residential installations would provide better information to designers and could lower overall project costs by eliminating ground-loop oversizing.

Technical Maturity and Current Developmental Status

The emerging technologies and strategies listed previously are either in limited practice or still under development for residential GHP applications. Once fully developed, the technologies would help lower the cost of GHP installations and improve long-term energy savings.

Barriers to Market Adoption

The overwhelming market barrier for GHPs in the U.S. is upfront cost leading to longer payback periods. Further, GHPs require considerable amounts of land to ensure proper ground heat transfer without damaging surrounding vegetation, and the ground-loop installation process can tear up a homeowner’s yard.

Energy Efficiency Advantages

Although they use many similar components, GHPs absorb and reject heat more efficiently than air-source technologies by using alternative heat sources and sinks. The moderate temperature of the ground results in lower temperature differences in both heating and cooling modes compared to those for air-source heat pumps, increasing efficiency.

Energy Savings Potential

Potential Market and Replacement Applications

From a technical standpoint, GHPs are applicable for most U.S. locations, although some urban areas may not have sufficient available land. Despite the impacts excavation and drilling have on a property, GHPs are often retrofit onto existing homes. These effects are lower for new homes without finished landscaping, especially for housing developments and multi-family buildings.

Energy Savings

The energy savings of GHPs depend on the efficiency of the indoor heat pump, outdoor heat exchanger, and other parasitic loads such as circulation pumps and will vary with each project. Although GHP ratings can exceed 25 EER for cooling and 12 HSPF for heating, these ratings are not typically representative of actual field performance because of ground-temperature variations, pumping and fan loads, etc.

Table G.3.3-2 summarizes general energy savings estimates from Goetzler et al. (2009). As a conservative estimate, we chose a unit energy savings of 30% compared to conventional central heating and cooling technologies. Although there are many retrofit installations, we chose a 25% replacement potential because of the site-specific issues with GHPs for both new and existing homes. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.25 Quads of natural gas and 0.23 Quads of electricity per year.

Table G.12-2. Energy Savings Estimates over Conventional Equipment (Goetzler et al. 2009)

GHP Efficiency	Conventional Equipment Type	Energy Savings (%)
Standard Efficiency	Air-Source Heat Pump	25-50%
	Gas Furnace/Air Conditioner	25-30%
Advanced Efficiency	Air-Source Heat Pump	50-70%
	Gas Furnace/Air Conditioner	50-60%

Cost and Complexity

The cost and complexity for each GHP system will vary with the configuration of the outdoor heat exchangers, installer experience, and other project-specific issues. The size and depth of the ground loops are determined by the underground thermal characteristics, with wetter, more compact soils permitting smaller, less costly, ground loops than loose, sandy soil permit. Designers without site-specific soil data often oversize ground-loops unnecessarily, adding to upfront cost. Open-loop and surface-water system designs can offer lower upfront costs compared to other strategies, but can only be used at a limited number of sites.

Liu (2010) states that GHPs typically cost between $4,600 - $7,000 per cooling ton installed, which is significantly higher than for conventional systems[30]. Even without the ground loops, the typical indoor heat pump has a 50-100% higher equipment cost than an air-source heat pump even though it uses similar components. The longer selling process and need for greater manufacturer assistance, as well as supply chain inefficiencies caused by lower manufacturing volumes, currently add to the overhead costs of GHPs. As GHPs become more prevalent, these cost differences may decrease.

Goetzler et al. (2009) estimate that residential GHPs have 5-10 year payback periods in the Northeast and Midwest compared to conventional air-source heat pumps and combination gas furnace/air conditioners. Paybacks in other areas of the country are typically longer.

Peak-Demand Reduction and Other Non-Energy Benefits

GHPs can offer substantial (10% and greater) peak-demand savings during the cooling season, but savings vary depending on the system design. When switching from gas-fired heating equipment, winter peak demand would increase. GHPs also eliminate fan noise typically associated with the outdoor compressor (except in hybrid configurations). By using a water/glycol-to-refrigerant heat exchanger, the refrigerant loop of indirectly coupled systems can be factory-sealed, so there is less chance of refrigerant leakage or improper charging.

Next Steps for Technology Development

Table G.3.3-3 presents the potential next steps to bring geothermal heat pumps to wider acceptance and achieve significant energy savings in the U.S.

Table G.12-3. Recommended Next Steps for the Development of Geothermal Heat Pumps

Initiatives	Lead Organization(s)
Develop a low-cost, reliable method to obtain ground thermal-conductivity measurements to more accurately size ground loops.	DOE, Industry Organizations, Academic Institutions
Conduct long-term monitoring of GHP installations with different outdoor heat exchanger designs to better understand the effects of ground-temperature fluctuations on efficiency over time.	DOE, Industry Organizations, Academic Institutions
Develop a validation process where new technologies and methodologies would be investigated, tested, and compared to ensure system performance for both installers and customers.	DOE, Industry Organizations, Manufacturers
Investigate alternative ground-coupling techniques, heat sources/sinks, and other high-efficiency technologies to compare their cost and heat-transfer characteristics with current designs.	DOE, Industry Organizations, Academic Institutions
Develop integrated design and simulation software to consistently size systems appropriately, and provide reasonable estimates on life cycle costs.	DOE, Industry Organizations, Academic Institutions
Publish best practices for system design, installation techniques, continued performance to increase understanding throughout the HVAC industry and raise awareness of new technologies.	DOE, Industry Organizations

[30] $1,450 - $2,300 for air-source heat pumps (Goetzler et al. 2009)

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G.13 Heat Pump for Cold Climates

Brief Description	Heat pumps for cold climates are air-source heat pumps with improved efficiency and capacity at lower temperatures (HSPF >9.5).	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.27 Quads/year	Commercially Available	Medium

Table G.3.4-1 summarizes heat pumps for cold climates for residential HVAC equipment.

Table G.3.4-1. Summary of the Characteristics of Heat Pumps for Cold Climates

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Heat Pump	
	Fuel Type	Electricity	
	Technical Maturity	Commercially Available	Heat pumps for cold climates are commercially available but have limited market penetration.
	Most Promising Applications	Homes in Cold Climate Region	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Minimum-standard air-source heat pump	13SEER/7.7 HSPF
	Annual Energy Consumption of Baseline Technology	1.08 quads/yr	Applies to northern US homes with existing duct work
	Applicability to Replacement Market	Medium	
	Technical Energy Savings Potential	0.27 quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	
	Non-Energy Benefits	• Improved comfort	
Next Steps for Technology	• Revise performance ratings for air-source heat pumps to better represent the performance of variable-speed heat pumps and the real-world use of supplemental resistance heating. • Perform large-scale demonstrations to validate real-world energy performance.		

Background

Technology Description

Air-source heat pumps are an electric HVAC system using air outside the building envelope as a heat source/sink for heating/cooling using a vapor-compression refrigeration system. Air-source heat pumps are typically installed in moderate to warm climates in the US, according to Kurt Roth (2009 [b]). Roth explains that two major issues limit air-source heat pumps in colder climates:

- Lower cooling loads compared to heating loads because increasing an air-source heat pump's size to meet northern heating demand is limited due to cooling-performance degradation associated with oversizing (Flynn 2012), and

- Decreasing capacity and COP of heating as outdoor temperatures decrease because of the increased temperature lift across the compressor.

Heat pumps for cold climates improve heating capacity and efficiency compared to standard air-source heat pumps for low-temperature applications. We define a cold-climate heat pump as an air-source heat pump with a HSPF of over 9.6[31]. Two designs have been introduced for cold-climate heat pumps:

- The booster air-source heat pump uses a two-cylinder compressor and an additional booster compressor to increase heating capacity. Hallowell International introduced the Acadia heat pump in 2007 using this design. During mild temperatures (above 42°F), the primary compressor runs on one cylinder. Below 42°F, the primary compressor operates on two cylinders to increase displacement and volumetric flow. When the temperature decreases to 30°F or lower, a second, booster compressor turns on for additional capacity.

- An air-source heat pump using a variable-speed scroll compressor modulates capacity to improve efficiency when heating and cooling. Carrier introduced its heat pump with GreenSpeed technology (GreenSpeed) in 2011 using a Copeland Scroll® variable-speed compressor optimized for heat pumps (Carrier 2012). The scroll compressor can 'overspeed', or run at speeds above the rated speed, to increase capacity during heating mode (Emerson 2012). Overspeeding provides additional capacity during heating mode, but does not overload the compressor because of the low suction densities (low mass flow of refrigerant) at lower temperatures.

Technical Maturity and Current Developmental Status

In the mid-1990s, Shaw Engineering developed a concept for an air-source heat pump they claimed eliminated the need for resistance heating in very cold weather (Stein 2006). In the early 2000s, Shaw Engineering licensed the technology rights to Nyle Systems, who developed four "Cold-Climate Heat Pump" prototypes. Shaw did not review Nyle's license for the low-

[31] We designated a heat pump for cold climate to perform 25% better than current DOE minimum standards in heating mode.

temperature heat pump technology, and instead licensed their technology to Hallowell International. Hallowell International then developed the cold-climate technology into their Acadia Heat Pump and, in 2007, began selling the units throughout the Northeast. Hallowell went out of business in May 2011 amid the economic downturn and rising customer dissatisfaction associated with faulty controls and compressor starting circuits (Russell 2011 [a]). A coalition of customers devised a solution to overcome of these technical issues; however, there was no further effort to refine this product line (Russell 2011 [b]).

In the late 2000s, Mitsubishi and Daikin each came out with ductless split-systems suitable for colder climates; however, both have limited availability in the United States. For discussion, see Ductless Split Systems.

In 2011, Carrier (2011) unveiled a heat pump for cold climates using Emerson's variable-speed Scroll® compressor.

NRCan (2011) conducted field testing featuring cold-climate heat pumps in a number of Canadian climate regions. Partnering with Ecologix Heating Technologies, NRCan investigated the capacity, efficiency, reliability, and cost-effectiveness of these systems as a market demonstration for the technology. Results were unavailable as of March 2012.

Heat pumps for cold climates are commercially available in the US, but have limited market penetration.

Barriers to Market Adoption

Heat pumps for cold climates must compete with natural gas, which is much cheaper than electricity[32].

Energy Efficiency Advantages

Heat pump for cold climates improve efficiency compared to standard air-source heat pumps by increasing capacity and COP at lower outdoor temperatures and modulating capacity to allow larger sizing (to better meet heating loads) while without incurring unacceptable cycling losses, reduced moisture removal and performance degradation in the cooling season. Additionally, heat pumps for cold climates can operate the heat pump to lower outdoor temperatures before it must cut out to avoid "cold blow", reducing the need for electric resistance heating.

Energy Savings Potential

Potential Market and Replacement Applications

The heat pump for cold climates would replace standard air-source heat pumps in cold climates (Northern U.S.). The heat pump for cold climates could also replace oil or gas furnaces in cold-weather homes with ductwork.

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[32] Based on data from EIA in January 2012. The average electricity price (per MMBtu) in the northeastern U.S. was three times that of the average northeastern natural gas price (per MMBtu).

Energy Savings

We estimate the heat pump for cold climates can save approximately 25% compared to a 13 SEER/7.7 HSPF air-source heat pump based on the following:

- According to Sachs, et al. (2009), a heat pump for cold climates (16 SEER/9.6 HSPF) provides an estimated energy savings of 26% over a standard-efficiency air-source heat pump (13 SEER/7.7 HSPF).
- Carrier (2011) rates their GreenSpeed line at 18-20 SEER and 12-13 HSPF.

Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.27 Quads of electricity per year.

Cost and Complexity

We estimate heat pumps for cold climates have a $2000-$4000 cost premium above standard-efficiency air-source heat pumps based on the following literature:

- EnergyIdeas (2007) reports that the installed cost of a heat pumps for cold climates is in the range of $8,000 to 12,000, including ducting, which suggests that the cost premium over a standard, conventional heat pump is in the range of $3,000 to $4,000 per installation. However, a more detailed breakdown of installed cost is not publicly available due to the reluctance of the manufacturer and distributor to disclose the cost information.
- Similarly, Sachs, et al. (2009) reports that Washington State University estimated a premium of $3000-4000, and Bonneville Power Association estimated $2000 in separate studies.
- Robert Zogg, in a phone call with Rich Flynn, a Carrier contractor (2012), noted a cost premium of $3000-$4000 for the Carrier GreenSpeed heat pump for cold climates.

Peak-Demand Reduction and Other Non-Energy Benefits

Heat pumps for cold climates, which heat over a larger range of temperatures, reduce peak demand in the winter by reducing the use of electric resistance heating.

Heat pumps for cold climates use a variable-speed compressor to modulate capacity, reducing cycling. This effect provides the consumer with a more constant indoor temperature.

Next Steps for Technology Development

Heat pumps for cold climates would benefit from a large-scale field test to demonstrate real-world energy performance.

Table G.3.4-2 presents the potential next steps to bring heat pumps for cold climates to wider acceptance and achieve significant energy savings in the U.S.

Table G.13-2. Recommended Next Steps for the Development of Heat Pumps for Cold Climates

Initiatives	Lead Organization(s)
Perform large-scale demonstrations to validate real-world energy performance	DOE, Manufacturers
Analyze reliability and performance of retrofitted heat pumps for cold climates versus those installed in new constructions	DOE, Manufacturers

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G.14 Hybrid Geothermal Heat Pump

Brief Description	Hybrid geothermal heat pumps (GHP) decrease the required size of the ground-coupled heat exchanger by using auxiliary, above-ground equipment peak loads. A hybrid GHP provides energy savings close to those for conventional GHPs, but lowers the installed cost significantly and reduces the long-term impacts of thermal imbalances on local ground temperature, providing improved economics.		
Technical Energy Savings Potential		**Technical Maturity**	**Cost/Complexity**
0.40 Quads/year		Emerging	High

Table G.3.5-1 summarizes hybrid geothermal heat pump for residential HVAC equipment.

Table G.3.5-1. Summary of the Characteristics of Hybrid Geothermal Heat Pump

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Central HVAC equipment	Air-source heat pumps and gas furnaces/air conditioners
	Fuel Type	Natural gas and electricity	
	Technical Maturity	Emerging	In practice, but only as custom designs
	Most Promising Applications	New construction, particularly housing developments, or multi-family buildings	Particularly homes in locations with unbalanced heating and cooling loads. Commonly retrofit for homes with existing duct systems.
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency central HVAC equipment	
	Annual Energy Consumption of Baseline Technology	1.91 Quads/yr	
	Applicability to Replacement Market	Low to Medium	25% based on the site-specific issues of this technology.
	Technical Energy Savings Potential	0.38 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	Can be very high in some installations.
	Non-Energy Benefits	None	
Next Steps for Technology	• Conduct field studies on different hybrid GHP designs for residential buildings and investigate the benefits of reducing long-term thermal buildup in soil by using balanced ground heat exchangers. • Develop best practices and design guides for hybrid GHP systems to raise awareness throughout the residential HVAC industry and end-users. • Develop a unitary condenser for hybrid GHP applications that would simplify		

	system design and installation. • Develop a packaged hybrid GHP incorporating a condenser coupled with direct-exchange ground-loops.

Background

Technology Description

A hybrid geothermal heat pump (GHP) utilizes both a ground-loop heat exchanger and an auxiliary heat exchanger or heating source to meet a building's thermal loads. This variation on the standard geothermal heat pump (GHP) reduces the required size of the underground heat exchanger, which provides the following advantages:

- **Lowers Upfront System Cost**
    - In areas of the country where seasonal heating and cooling loads are significantly different, the ground heat exchanger must be sized to provide enough capacity to meet peak building loads. This increases the size of the ground heat exchanger to meet the peak needs that occur only a few hours a year. By adding a less-expensive supplementary system to meet peak loads, system designers can decrease the size of the ground heat exchanger, reducing project costs.

- **Maintains Thermal Balance Better**
    - After a number of years, when more heat is rejected to the ground than extracted (or vice versa), the temperature of the soil increases (or decreases), which lowers system efficiency over time. Hybrid GHPs maintain better long-term thermal balance by using auxiliary heat exchangers and heating sources. Sustaining an adequate thermal balance maintains operational performance and reduces equipment wear.

Figure G.3.5-1 provides a schematic for a sample hybrid GHP system. Most hybrid GHP installed systems use closed-loop designs, rather than direct-exchange of refrigerant[33]. For the majority of the year, the smaller ground heat exchanger meets the building loads, but during peak building loads, the auxiliary systems of the hybrid GHP provide the extra necessary capacity. During cooling mode, an air-cooled condenser may reject the additional heat. During heating mode, an electric-resistance heater, furnace, or boiler augments the capacity of the ground-loop system. This way, the system realizes the efficient performance afforded by ground coupling during most of the year, at lower upfront cost.

[33] See Section G.3.3 on GHPs.

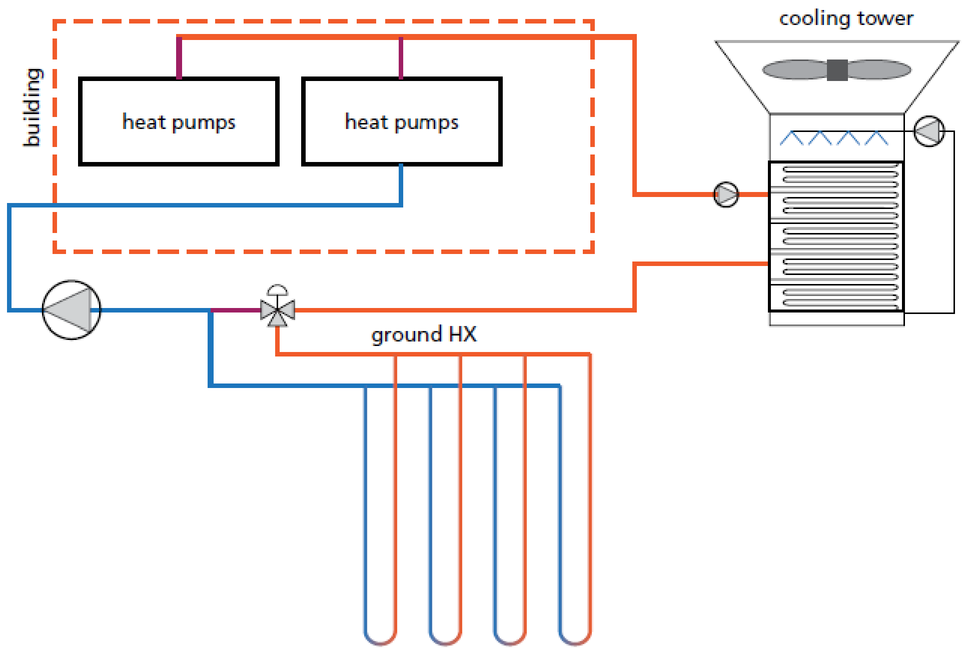

Figure G.14-1. Sample Hybrid Geothermal Heat Pump with Cooling Tower[34]

Source: Hackel (2011)

Most current hybrid GHP installations consist of commercial or large multi-family buildings using cooling towers to augment the ground-loops during summer cooling loads. For most residential applications, hybrid GHPs would use a dry heat exchanger (much like a split-system condenser) because of maintenance and Legionella concerns relating to cooling towers. For direct-exchange GHPs, a specially designed condenser could directly reject heat from the refrigerant.

Technical Maturity and Current Developmental Status

This is an emerging technology with limited availability in the U.S. market today, and limited published research exists on hybrid GHPs for residential applications. Primarily designed for commercial buildings, very few GHP projects use the hybrid approach, even though the additional components (cooling tower, boiler, etc.) are available. Through a project funded by DOE and NIST in 2011, Hackel and Pertzborn of the University of Wisconsin – Solar Energy Lab developed a modeling system for hybrid GHP to aid designers (Hackel and Pertzborn 2011).

Barriers to Market Adoption

Installation costs, while lower than those for traditional GHPs, may still be too high for many home owners. While HVAC designers and installers have become more familiar with GHP technology, hybrid systems pose another degree of complexity. There are few design standards

[34] Cooling towers are common for commercial hybrid GHPs, but most residential systems would use dry-cooling methods.

for hybrid GHPs and no packaged products currently on the market, so each project requires a custom design that increases project cost.

Energy Efficiency Advantages

Similar to a traditional GHP, the hybrid system rejects heat to the ground in the cooling mode, and absorbs heat from the ground in the heating mode. Because the ground maintains a relatively steady temperature and has a higher thermal mass, it is a more efficient heat source/sink than air. Hybrid GHP systems utilize the ground as the heat sink/source for off-peak operation, and utilize supplementary heat exchangers or heating systems for additional capacity during peak loads. Because the ground heat exchangers provide the majority of space conditioning, the hybrid system provides similar unit energy savings to a traditional GHP system.

Energy Savings Potential

Potential Market and Replacement Applications

Hybrid GHPs are applicable for both new and existing buildings in most U.S. locations, if there is sufficient land area. Installing ground-loops in new housing developments or for multi-family buildings minimizes the disturbance to existing landscaping, and may be more attractive than retrofit applications. This technology provides the largest cost savings over GHPs in locations that have unbalanced heating and cooling loads. Because the size of the ground heat exchanger is minimized, hybrid GHPs could be used on homes with less available land.

Energy Savings

Hackel and Pertzborn (2011) modeled and tested a number of hybrid GHP systems for commercial and multi-family buildings and found energy savings of 15-40% over conventional systems. The energy savings of hybrid systems generally matched that of traditional GHP systems.

We chose a unit energy savings of 20% as a conservative estimate over conventional central heating and cooling technologies once accounting for the energy consumption of the auxiliary systems. Compared to 25% for GHPs, we chose a 30% replacement potential[35] because hybrid GHPs alleviate some of the site-specific issues with GHPs for both new and existing homes through the smaller ground heat exchanger. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.20 Quads of natural gas and 0.18 Quads of electricity per year.

Cost and Complexity

Compared to conventional air-source heat pumps and combination gas furnace/air conditioners, installation of the ground heat exchanger substantially raises the initial costs for conventional GHPs, often 30-50% higher[36]. However, the initial cost premium would be lower for a hybrid system than a standard GHP because the smaller ground-loop requirement, which substantially offsets the additional cost of the auxiliary equipment.

[35] Compared to 25% for GHPs

[36] See Section G.3.3 for more information.

Hackel and Pertzborn (2011) estimated a 50% lower incremental cost for hybrid GHPs compared to standard GHP designs in locations with unbalanced thermal loads. Based on this, the installed-cost premium for the hybrid GHP would be about 25-50% compared to an air-source heat pump[37], or about $2,300 - $3,500 installed cost for a typical single-family home.

Peak-Demand Reduction and Other Non-Energy Benefits

Although peak-demand reduction will vary for each site, FEMP (2000) cites examples of significant demand savings. Because of the additional auxiliary components, peak-demand reduction would be expected to be less than conventional GHPs. Hybrid GHPs can minimize long-term underground heat gain better than conventional GHPs, further reducing demand during peak cooling loads.

Next Steps for Technology Development

Table G.3.5-2 presents the potential next steps to bring hybrid geothermal heat pump to wider acceptance and achieve significant energy savings in the U.S.

Table G.14-2. Recommended Next Steps for the Development of Hybrid Geothermal Heat Pump

Initiatives	Lead Organization(s)
Conduct field studies on various hybrid GHP designs for residential buildings and investigate the benefits of reducing long-term thermal buildup in soil by balancing ground heat exchange.	DOE, Industry Organizations, Academic Institutions,
Develop best practices and design guides for hybrid GHP systems to raise awareness throughout the residential HVAC industry and end-users.	DOE, Industry Organizations,
Develop an air-source heat exchanger for hybrid GHP applications that would simplify system design and installation.	DOE, Manufacturers
Develop a packaged GHP incorporating a condenser coupled with direct-exchange ground-loops designed for lower installation costs.	DOE, Manufacturers

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[37] $1,450 - $2,300 for air-source heat pumps (Goetzler et al. 2009)

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G.15 Integrated Heat Pump

Brief Description	The integrated heat pump (IHP) supplies space heating, space cooling, and domestic hot water, on demand, using a vapor-compression heat pump.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.55 Quads/year	Emerging	High

Table G.3.6-1 presents a summary of integrated heat pumps for residential HVAC equipment.

Table G.3.6-1. Summary of the Characteristics of Integrated Heat Pumps

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Heat Pump	
	Fuel Type	Electricity	
	Technical Maturity	Emerging	IHPs were introduced in the late 1980s but failed on the market. IHPs have some availability overseas, and there are some limited initiatives in the U.S. to reintroduce IHPs to the market.
	Most Promising Applications	Homes with installed electric heat pump	We assume IHP will compete with electric heat pumps because of the high first cost of IHP.
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard efficiency air-source electric heat pump and electric domestic water heater	
	Annual Energy Consumption of Baseline Technology	3.70 Quads/year	
	Applicability to Replacement Market	Medium	Homes with electric HP and electric water heating
	Technical Energy Savings Potential	0.55 Quads/year	50% estimated energy savings with 20% estimated U.S. heat pump market share
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	Peak-demand reduction is associated with HVAC energy savings
	Non-Energy Benefits	None	
Next Steps for Technology	• Monitor results of ORNL field-testing • Study ductless IHP viability in U.S. market		

Background

Technology Description

In a 2007 ORNL report for Integrated Heat Pump (IHP) System Development, Murphy et al. note three changes that will affect HVAC and water heating equipment.

- Tighter building envelopes reduce energy required to heat/cool a home. However, additional energy is necessary to provide controlled ventilation because of lower air infiltration.
- Lower energy requirements associated with improved building envelopes and more efficient HVAC equipment reduces the necessary capacity of heating and cooling equipment.
- Domestic water-heating demand, which is occupancy-dependent, is unchanging. Therefore, a larger percentage of energy demand for HVAC/WH equipment is water-heating demand.

In the U.S., vapor-compression heat pumps have successfully provided comfort conditioning for millions of homes, and their use for water heating (heat pump water heaters) has increased in recent years. As vapor-compression heat pumps improve through use of advanced controls and variable-speed technology, heat pumps could combine these large home energy needs using a single thermal system.

An integrated heat pump (IHP) supplies space heating, space cooling, or domestic hot water on demand using a vapor-compression heat pump. IHPs may distribute space conditioning using an air handler (using either a hydronic or DX coil) and ductwork, or using an in-floor radiant system. When an IHP provides hydronic space heating/cooling, it is sometimes called a reverse-cycle chiller. During the cooling mode, the heat pump rejects the refrigerant’s heat to a heat exchanger, which heats the water tank (if the tank can accommodate additional heating). This condenses the refrigerant more efficiently, using excess energy to heat domestic water. Additionally, excess heat in the cooling and dehumidification mode can condition ventilation air and heat water.

According to Murphy et al. (2007), ORNL designed an IHP system for residential applications. The ORNL design uses, “several modulating components including a modulating compressor, one multiple-speed pump, two variable-speed fans, and heat exchangers — two air-to-refrigerant, one water-to-refrigerant, and one air-to-water--to provide space conditioning and water heating as part of an air-source or geothermal heat pump and a storage water heater. While some IHP designs alternate between space conditioning and water heating, the ORNL design permits simultaneous space conditioning and water heating.

Technical Maturity and Current Developmental Status

IHPs currently have limited availability in the U.S. market. Development of IHPs began in the late 1980s with EPRI and Carrier’s “HydroTech 2000”, and Artesian Building Systems’ “Mac=Pac.” Both products failed to gain traction due to their high initial costs (DiChristina 1989) and were removed from the market after selling only a few hundred units (Murphy 2007). In the early 1990s, Nordyne introduced the PowerMiser integrated heat pump using the same concept as Carrier and Artesian, but removed it from the market within a few years due to lack of sales (Murphy 2007).

Japanese manufacturers developed air-source IHPs using R-744 (CO_2) known as "Eco Cute" heat pumps (also the name of the Japanese heat-pump water heaters). One example, Daikin, recently introduced the 'Altherma', an IHP using R-410A refrigerant. Because advancements in heat-pump efficiency have improved the payback, these units have sold very well in Asia; however, Japanese systems are ductless, which may limit their applicability in the U.S. where most electric heat pumps use ductwork. Still, ductless IHPs are applicable as replacements for homes not having ductwork.

ORNL, in conjunction with DOE's near-zero-energy housing project, has developed a geothermal IHP for ducted systems in the U.S. ORNL is also working with two manufacturers to develop air-source IHPs for field testing. No manufacturers have made this design to commercial availability to date.

Barriers to Market Adoption

High first cost limits market adoption of IHPs. Typically, heat pump contractors and water heating contractors are part of different trades (heat/cooling and plumbing). Limited overlap may slow market adoption in the U.S. Additionally, U.S. hopes with the outdoor unit far from the water heating unit may not be able to install an IHP.

Energy Efficiency Advantages

Using an on-demand heat pump for both space conditioning and water heating provides heat-pump efficiencies for water heating, plus utilizes reject heat for water heating during the cooling season, providing additional efficiency benefits.

Energy Savings Potential

Potential Market and Replacement Applications

With standard air-source heat pumps, IHPs would be best suited for moderate to warm climates because of limitations of heat pumps in colder weather. As air-source heat pumps improve in cold-climate applications, IHPs would increase applicability in cold climates (see Section G.3.4 for additional information). Because there are various configurations for IHPs, this technology can be installed in homes with either hydronic or forced-air heating systems. Ductless IHPs can be installed in homes not having ductwork. Due to high projected costs for IHP systems, IHPs are most applicable for end-of-life equipment replacements and new construction. Additionally, in replacement applications, IHPs will likely primarily compete with electric HVAC/WH equipment because of the reduced energy-cost savings and added installation costs associated with fuel switching.

Energy Savings

We estimate the IHP can effectively lower HVAC energy use by about 50% (accounting for water-heating savings) compared to a 13SEER/7.7HSPF air-source heat pump and a 0.9EF electric water heater, based on the following estimates from literature:

- Baxter et al. (2008) claim their ORNL-design IHP using R-410A achieves 46-67% HVAC energy savings in a variety of US locations compared to a standard-efficiency heat pump (SEER 13/HSPF 7.7) and electric water heater (0.9 EF).

Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.55 Quads of electricity per year.

Cost and Complexity

We estimate integrated heat pumps have a $2500 - $3500 installed-cost premium above standard-efficiency air-source heat pumps and electric water heaters based on the following:

- Baxter et al. (2008) claim their ORNL-design IHP using R-410A has a $2500 - $3500 installed-cost premium compared to a standard-efficiency heat pump (SEER 13/HSPF 7.7) and electric water heater (0.9 EF).

Peak-Demand Reduction and Other Non-Energy Benefits

If displacing electric space-conditioning and water-heating technologies (including other heat pumps), there would be a demand savings associated with the reduction in HVAC energy use. However, the portion of savings associated with lower condensing temperatures when simultaneously performing space cooling and water heating may not contribute much to demand reduction because water heating typically takes place outside of peak-demand periods.

Next Steps for Technology Development

ORNL is currently working on results for geothermal IHP field testing, and results should be monitored upon completion. ORNL is also working through two CRADAs on air-source IHPs, which have not yet been prototyped. Field-testing is planned in the short-term future.

Ductless IHP may provide significant energy savings for U.S. homes, but are not yet available to U.S. consumers. A study to determine the viability of ductless IHP in the U.S. may benefit the technology.

Table G.3.6-2 presents the potential next steps to bring integrated heat pumps to wider acceptance and achieve significant energy savings in the U.S.

Table G.15-2. Recommended Next Steps for the Development of Integrated Heat Pumps

Initiatives	Lead Organization(s)
Monitor results of the ORNL geothermal heat pump field tests for validation of ducted IHPs in the U.S.	ORNL, DOE, Manufacturers, Industry Organizations, Utilities
Monitor progress of the ORNL air-source heat pump prototype and field tests for validation of ducted IHPs in the U.S.	ORNL, DOE, Manufacturers, Industry Organizations, Utilities
Study ductless IHP and determine viability in the U.S. market through targeted case studies.	ORNL, DOE, Manufacturers, Industry Organizations, Utilities

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G.16 High-Performance System Design and Restoration Technology Options

G.17 Aerosol Duct Sealing

Brief Description	When introduced in duct systems, aerosol duct sealants selectively deposit around holes, plugging leaky ducts without having to locate and access the holes. By decreasing duct leakage, a greater percentage of the thermal energy reaches its intended space, reducing thermal and fan energy consumption.		
Technical Energy Savings Potential		**Technical Maturity**	**Cost/Complexity**
0.30 Quads/year		Commercially Available	Medium

Table G.4.1-1 summarizes aerosol duct sealing for residential HVAC equipment.

Table G.4.1-1. Summary of the Characteristics of Aerosol Duct Sealing

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Ducted HVAC systems.	
	Fuel Type	Electricity and Natural Gas	
	Technical Maturity	Commercially Available	
	Most Promising Applications	Homes where the ducts are located outside the conditioned space	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency central HVAC equipment	
	Annual Energy Consumption of Baseline Technology	2.95 Quads/yr	
	Applicability to Replacement Market	High	Primarily designed for existing homes.
	Technical Energy Savings Potential	0.30 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	High	Approximately 25%.
	Non-Energy Benefits	• Improved occupant comfort • Improved indoor air quality • Noise reduction	
Next Steps for Technology	• Establish utility incentive and awareness programs for duct-leakage testing and remediation, highlighting aerosol duct sealing. • Conduct follow-up evaluations and testing on past customers to determine the long-term performance of aerosol sealants. • Incorporate duct-leakage testing and sealing as part of standard maintenance		

	practices either through quality maintenance initiatives, building codes, or industry standards.

Background

Duct-Leakage Problem

Most residential HVAC systems deliver conditioned air to the home using a series of ducts. Typically made from sheet metal, ducts are usually situated behind walls, under floors, in crawlspaces, or in attics. Over time, small holes and cracks can form in the joints that connect the duct connections because of poor installation, physical movement, or thermal cycling. When this occurs, the conditioned air escapes through these holes. If the duct is located outside the conditioned space, the thermal energy and the fan energy needed to circulate that air volume are both lost.

Although the problem of duct leakage was identified long ago, not until a 1986 LBNL study did the prevalence of duct leakage become apparent (LBNL 2012). Over the years, researchers have concluded that, for a typical residential home, 15-30% of HVAC energy consumption is lost to duct leakage, with much higher percentages in some instances. Numerous methods have been developed to measure duct leakage and repair leaks. Diagnostic tools such as the duct pressurization, Delta-Q, or tracer-gas tests try to quantify duct leakage and help locate leaks. If leaks are located and accessible, HVAC service technicians can repair ducts by applying mastic sealants to cracks. If, however, ducts are not accessible or if the leaks are too small to identify, aerosol duct sealing can reduce duct leakage more effectively.

Technology Description

Aerosol duct sealing systems introduce a vinyl-acetate adhesive into the ductwork in the form of an aerosol spray. Driven by a fan, the moving air stream suspends the aerosol until it reaches the duct holes, so it doesn’t deposit on the interior of the duct. The spray travels through the ductwork and leaks out through cracks and holes. When the aerosol leaves the ducts, the adhesive sticks to the edges of the hole, accumulating over time until the hole is sealed. While this process is most effective for holes ¼ in. and smaller, the system can plug holes up with a diameter of 5/8 in. The process takes around 4-8 hours and can reduce existing duct leakage by over 90%.

Originally developed at LBNL in the 1990s, Aeroseal, LLC commercialized this technology , and they license it to local contractors and energy service companies across the country. The system itself consists of (Aerosol 2012):

- Adhesive-aerosol sealant
- Aerosol atomizer to inject the sealant though a hole cut into the supply/return duct or air-handler plenum
- Foam plugs to seal the supply and return grills
- Computer with monitoring software

Figure G.4.1-1 shows the different components in an aerosol duct sealing system.

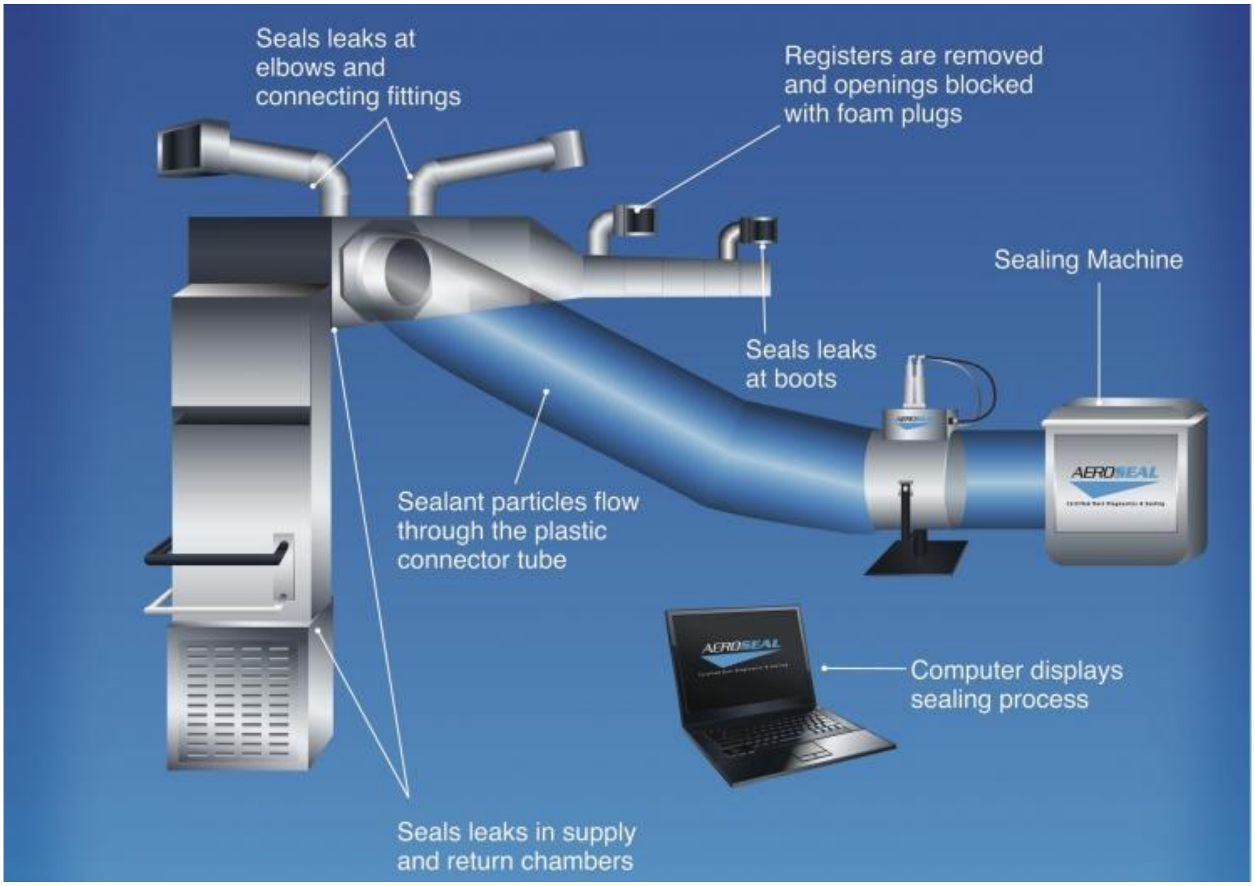

Figure G.17-1. Aerosol Duct Sealing System

Source: O'Neill (2011)

Technical Maturity and Current Developmental Status

Aeroseal, LCC has successfully commercialized this technology and seals thousands of homes each year. Purchased by Carrier Corporation in 2001, Aeroseal was acquired in 2011 by a number of investors that formed the JMD Corporation, and who returned control of Aeroseal back to its founder Mark Modera. Aeroseal has since announced an increased effort to license to dealers throughout the U.S. to offer aerosol duct sealing to their heating and cooling customers. Additionally, a number of utility efficiency programs have acknowledged and promoted aerosol duct sealing.

Barriers to Market Adoption

Aerosol duct sealing does not work for large cracks or disconnected ductwork, which require manual repair. The upfront cost of duct sealing and concern over off-gassing from the sealant may dissuade some homeowners from using this system.

Energy Efficiency Advantages

Duct leakage results in higher HVAC energy consumption because air leaks remove conditioned air from the system, requiring the HVAC system to expend more energy producing additional conditioning and airflow. Aerosol duct sealing reduces duct leakage allowing a higher percentage of conditioned air to reach its intended location.

Energy Savings Potential

Potential Market and Replacement Applications

The aerosol duct sealing system is intended any new or existing home using ductwork to move conditioned air. Some building codes, such as California Title 24, require duct-leakage testing during the installation of HVAC equipment or major renovations. If the testing reveals excessive duct leakage, the building code requires duct remediation, which could be accomplished through aerosol duct sealing.

Energy Savings

According to Hamilton et al.(2003), Aerosol duct sealing can reduce system energy consumption by 4% to 9%, by reducing the duct-leakage rate down between 2% and 3% (from typical rates of 10% to 20%).

Modera (2008) stated that a 20% duct leakage rate results in an approximate 15% reduction in SEER rating. Based his experience with aerosol duct sealants, the process results in system energy savings of 10% for basement ducts, and 15-20% for ducts located in attics or crawlspaces. Additionally, eliminating duct leakage results in 25% peak-demand savings.

We chose a unit energy savings of 10% based on the assumptions that aerosol duct sealing could reduce leakage by 90% for a system with a 30% duct leakage rate and 25% of the leaked airflow conditioned the living space. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.13 Quads of natural gas and 0.17 Quads of electricity per year.

Cost and Complexity

According to Hamilton et al. (2003), implementation of an aerosol duct sealing process costs about $0.40 per square foot of floor space.

According to Sachs et al. (2004), the average of cost of using an aerosol duct sealing system in residential homes was slightly over $1,000 (for a study of 121 Sacramento homes). They estimated a mature market cost of $500 to $900 per residence.

Peak-Demand Reduction and Other Non-Energy Benefits

For technologies that can provide air-conditioning, we assumed that savings associated with peak demand would mirror savings associated with overall demand. We assumed that peak demand highly correlates with air-conditioning demand. Sealing ducts results in improved occupant comfort, indoor air quality, and possible noise reduction.

Next Steps for Technology Development

Table G.4.1-2 presents the potential next steps to bring aerosol duct sealing to wider acceptance and achieve significant energy savings in the U.S.

Table G.17-2. Recommended Next Steps for the Development of Aerosol Duct Sealing

Initiatives	Lead Organization(s)
Establish utility incentive and awareness programs for duct leakage testing and remediation, highlighting aerosol duct sealing.	Utilities
Conduct follow-up evaluations and testing on past customers to determine the long-term performance of the aerosol sealants.	DOE, Manufacturers
Incorporate duct-leakage testing and sealing as part of standard maintenance practices either through quality maintenance initiatives, building codes, or industry standards.	DOE, Industry Organizations

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G.18 Regular Maintenance

Brief Description	Regular maintenance is servicing of HVAC equipment as recommended by the manufacturer to, in part, minimize efficiency degradation over time.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.83 Quads/year	Emerging	Medium

Table G.4.2-1 presents a summary overview of regular maintenance for residential HVAC equipment.

Table G.4.2-1. Summary of the Characteristics of Regular Maintenance

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	All HVAC Systems	
	Fuel Type	All Fuel Types	
	Technical Maturity	Commercially Available	
	Most Promising Applications	Existing HVAC systems	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency HVAC equipment	
	Annual Energy Consumption of Baseline Technology	6.38 Quads	
	Applicability to Replacement Market	High	Applicable to all existing HVAC Maintenance could supplement all HVAC installations.
	Technical Energy Savings Potential	0.83 Quads	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	
	Non-Energy Benefits	• Improved equipment longevity • Improved comfort, • Improved indoor air quality • Noise reduction	
Next Steps for Technology	• Quantify better the energy savings of regular maintenance • Educate consumers about the benefits of having regular maintenance performed on their HVAC systems		

Background

Technology Description

HVAC systems require periodic maintenance to help ensure safe operation, long life and to maintain efficiency. Manufacturers recommend homeowners, building owners, or certified contractors perform regular inspection of HVAC equipment. Regular maintenance refers to periodic inspections; typical recommended intervals for routine maintenance are yearly for heating or cooling only and twice a year for heat pumps. Table G.4.2-2 includes some recommended preventive maintenance measures.

Table G.4.2-2. Types of Preventive Maintenance Measures

Preventive Maintenance Measure	Typical Efficiency Improvement[a]	Description
Clean Evaporator and Condenser Coils	2-4%	Dust and other substances inhibit heat transfer and air flow in heat exchangers, and can reduce air conditioner efficiency and capacity by 2-4%. (Siegel, 2002)
Inspect Condensate Drains for Clogs and Scale	b	A clogged drain can reduce HVAC performance, cause water damage in the house, and increase indoor humidity levels. (ENERGY STAR, 2012)
Clear Debris from Condenser Coil Grills	b	(Trane, 2012)
Maintain Proper Refrigerant Charge	5% to 16%	Over time, refrigerant charge may leak from the HVAC system. Maintaining refrigerant charge can improve the life and efficiency of the system. (Jacobs, 2003)
Inspect Heat Exchanger	4-12%	Heat exchange fouling causes slower heat exchanger rates. A 1/16th inch layer of soot or mineral deposits can increase energy use 4 or 12%, respectively. (Colorado Springs Utilities, 2009)
Change Air Filters	b	Dirty/clogged air filters can restrict airflow causing equipment to work harder, reducing life and efficiency. (ENERGY STAR, 2012)
Clean and Fix Blower Components	15%	Proper airflow is required to maintain optimal efficiency. Low airflow can reduce system performance up to 15%. (ENERGY STAR, 2012)
Calibrate Automatic Control Sensors	10%+	Ensure the correct automatic control-sensor readings (for ambient conditions and HVAC settings) and calibrate if necessary. (Colorado Springs Utilities, 2009)

a Potential reduction in performance if regular maintenance not performed.
b Literature search did not reveal quantified performance implications.

Unfortunately, many homeowners forego preventive maintenance; homeowners resolve issues in response to discomfort or system failure. Robert Franklin, in a letter to the US Consumer Product Safety Commission (Franklin, 2000), cited an Edison Electric Institute survey that found that two-thirds of homeowners did not have a service contract and had not hired a contractor for service in the previous 5 years.

Technical Maturity and Current Developmental Status

This technology is commercially available in the United States. Gas and electric utilities, manufacturers, and private contractors all provide regular maintenance services for HVAC equipment; however, many consumers still do not practice regular maintenance.

Table G.4.2-3 presents examples of current initiatives promoting regular maintenance in the U.S.

Table G.4.2-3. Examples of Current Promotion of Regular Maintenance

Initiatives	Lead Organization(s)
Website Mention of Residential HVAC Maintenance	Manufacturers (Trane, Carrier)
Web-based Maintenance Checklist	EPA (ENERGY STAR)
Protection and Maintenance Plans	Private Organizations, Utilities

Barriers to Market Adoption

The benefits of regular preventive maintenance are difficult to quantify without careful monitoring and benchmarking. Also, there is no assurance that a maintenance call will improve efficiency of a given HVAC system.

Energy Efficiency Advantages

Without regular maintenance, system performance may degrade. Regular maintenance helps ensure proper HVAC system performance, including maintaining expected efficiencies for space heating and cooling.

Energy Savings Potential

Potential Market and Replacement Applications

Regular maintenance would benefit all residential HVAC systems, regardless of size or location. Regular maintenance is applicable for existing residential HVAC systems that do not already receive regular maintenance.

Energy Savings

Table G.4.2-2, above, shows a breakdown of typical energy savings by maintenance activity. Energy savings may not be additive. We estimate a unit energy savings of 13% based on cleaning the condenser coil and performing one other regular maintenance measure. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.43 Quads of natural gas per year and 0.40 Quads of electricity per year.

Cost and Complexity

Some homeowners have service contracts with a local HVAC company to perform maintenance twice a year on the heating and cooling equipment. Residential HVAC service plans are readily available, and contactors are available to perform regular maintenance.

Franklin (2000) estimated the cost of a service contract for a furnace to be $130-340 ($2011) per year.

A service contract with J.E. Shekell Inc., costs $348 per year, including parts and labor for electric heat pumps for gas heating systems (J.E. Shekell Inc. 2012). The service contract provides a spring and fall system tune-up, and includes:

- Evaporator and condenser coil inspection
- Check electronic controls and connections
- Clean condenser coil and blower, and change air filter (if necessary)
- Examine parts for wear
- Check operating pressures and refrigerant levels
- Lubricate motor
- Flush drain and check drain pan.

Peak-Demand Reduction and Other Non-Energy Benefits

Performing regular maintenance keeps HVAC equipment performing properly, and can help improve comfort by reducing temperature fluctuations and noise. Maintaining equipment improves the longevity of the HVAC system, reducing the likely number of repairs or replacements.

Next Steps for Technology Development

Educating consumers about the benefits of regular maintenance could improve maintenance practices, encouraging efficiency savings and peak-demand reduction. Advanced diagnostics and energy management software could notify homeowners, maintenance staff or contractors of any abnormalities. Additionally, integrating advanced diagnostic software into HVAC equipment could simplify regular maintenance for the homeowner.

Table G.4.2-4 presents the potential next steps to promote regular maintenance and achieve significant energy savings in the U.S.

Table G.18-4. Recommended Next Steps to Promote Regular Maintenance

Initiatives	Lead Organization(s)
Improve consumer education on regular maintenance.	DOE, Industry Organizations, Utilities
Integrate HVAC monitoring into Energy Management Systems (see Section G.5.2, Home Energy Management Systems, for discussion)	Manufacturers
Investigate designing features for residential HVAC to simplify and improve regular maintenance	DOE, Manufacturers, Industry Organizations

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G.19 Retrocommissioning

Brief Description	Residential retrocommissioning (RCx) is the process of assuring an existing home achieves energy efficiency that it was designed to achieve.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
1.62 Quads/year	Commercially Available	Medium

Table G.4.3-1 summarizes RCx for residential homes.

Table G.4.3-1. Summary of the Characteristics of Retrocommissioning

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	All HVAC	RCx includes other building systems, including lighting, water heating, and building envelope.
	Fuel Type	All	
	Technical Maturity	Emerging	
	Most Promising Applications	Existing homes	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency HVAC equipment	
	Annual Energy Consumption of Baseline Technology	8.12 Quads/yr	
	Applicability to Replacement Market	High	RCx is comprehensive and includes building systems other than HVAC, as noted above.
	Technical Energy Savings Potential	1.62 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	High	
	Non-Energy Benefits	• Improved air quality • Improved occupant comfort • Longer equipment/building lifetime	
Next Steps for Technology	• Perform residential case studies and quantify energy savings and benefits of residential RCx • Provide services for residential consumers to retrocommission their homes		

Background

Technology Description

Many homes in the United States do not perform at optimal energy efficiency levels. In "Residential Commissioning: A Review of Related Literature" for LBNL, C.P. Wray et al. (2000) the authors note that most home HVAC systems perform well below designed specifications. Two homes built at the same time in the same neighborhood may have different energy performance. Wray cites a study that found variations of 50% in envelope leakage between two homes "with the same design, builder, and subcontractors within the same subdivision." Wray concludes, "Most homes are field assembled from a large number of components and there is no consistent process to identify related energy and non-energy problems or to correct them."

Commissioning is the process of verifying a building's systems meet intended design specifications during construction. Commissioning ensures the proper operation of electrical, mechanical, and control components to optimize HVAC system function. Commissioning is practiced in commercial buildings to reduce risk and save money during the construction of a building. Commissioning ideally begins in the planning phase of a commercial building construction, but may begin any time prior to occupancy, and is performed throughout the building process to ensure all systems function properly separately and together.

Residential commissioning follows the same principle as commissioning for commercial buildings, but is rarely practiced in the United States. Residential commissioning includes many elements already practiced in homes (regular maintenance, duct-leakage testing, etc.); however, they typically do not look at the whole house as a system, according to the Public Interest Energy Research Program. (PIER, 2005)

Although commissioning is done for some new-building construction, other types of commissioning can be completed at various stages of a building's life.

- RCx is the process of verifying an existing building's systems meet intended design specifications on buildings that have not previously been commissioned.

- Recommissioning is the process of re-verifying that an existing building's systems meet intended design specifications, or verifying a retrofit on an existing building that has previously been commissioned. For the purposes of this study, recommissioning also includes super-commissioning, which is sometimes referred to as the process of improving a building's systems beyond initial design specifications.

Residential RCx makes recommendations for existing homes to bring HVAC systems, as well as other building systems (e.g., lighting systems, building envelope, and water heating), to intended design specifications or better. Because most homes do not perform as designed, residential RCx can reduce energy consumption 20% on average by repairing errors during construction, recommending upgraded infrastructure, or performing neglected maintenance (see Section G.4.2 on regular maintenance).

According to Matson et al. (2002), residential RCx can be divided into three main phases:

- Audit Phase: Current conditions and performance of the house and HVAC system are evaluated.
- Commissioning Phase: Systems are tuned to improve efficiency.
- Opportunity Phase: Additional energy efficiency measures are identified for future implementation.

Technical Maturity and Current Developmental Status

Residential RCx is emerging and not widely practiced in the U.S. In the last 1990s and early 2000s, LBNL and other organizations created literature on residential retrocommissioning. Literature for residential RCx is limited after 2005 and recent literature focuses on commercial commissioning and RCx.

Barriers to Market Adoption

Residential RCx is largely unknown as an option for residential HVAC. Benefits of RCx are not quantified, and it is difficult for homeowners to spend money without understanding potential benefits.

Energy Efficiency Advantages

According to Matson et al. (2002) residential RCx promotes any or all of the following HVAC activities:

- Improved insulation
- Building envelope tightening
- Improving ductwork (repairing duct leakage and insulation)
- Refrigerant charge and air-handler airflow correction
- Repair/upgrade HVAC equipment
- Improved temperature set-points (programming the thermostat)

Energy Savings Potential

Potential Market and Replacement Applications

Retrocommissioning is applicable for existing homes in the U.S. Older homes would benefit the most from RCx, whereas more recent, energy-efficient homes would benefit the least.

Energy Savings

Matson et al. (2002) modeled the energy savings to be 15-30% for existing homes including corrective measures during a single site visit (commissioning phase). Taking advantage of additional, possibly more complex, opportunities could result in 50-75% savings (opportunity phase).

Based on the above report, which is the only credible source we uncovered, we used 20% as representative of typical residential RCx savings. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.67 Quads of natural gas per year and 0.96 Quads of electricity per year.

Cost and Complexity

The costs of residential RCx can vary widely depending on the size and age of the house and its HVAC equipment. Matson, et al., indicate that the fixed costs of commissioning equipment to be about $10,000 to $25,000. Matson, et al. (2002) estimate commissioning a house to take 4-6 labor hours for well-trained technicians. For the purposes of our estimate, we will assume labor costs for RCx are $100 per hour and each RCx amortizes 1% of the fixed costs. Based on 4-6 labor hours, we estimate RCx costs $500 - $850 for a typical single-family home, not including replacements or extra parts.

Peak-Demand Reduction and Other Non-Energy Benefits

Residential RCx reduces peak demand in proportion to its HVAC energy savings.

Matson et. al (2002) claim RCx improves indoor air quality, consumer comfort, and improved building/HVAC longevity.

Next Steps for Technology Development

Residential RCx is not widely performed throughout the U.S. Benefits or examples of RCx for residential RCx are not well documented, and quantifying the energy savings of residential RCx would allow consumers to understand technology benefits.

Table G.4.3-2 presents the potential next steps to bring retrocommissioning to wider acceptance and achieve significant energy savings in the U.S.

Table G.19-2. Recommended Next Steps for the Development of Retrocommissioning

Initiatives	Lead Organization(s)
Perform residential case studies and quantify energy savings and benefits of residential RCx.	DOE, Manufacturers, Industry Organizations, Utilities
Provide services for residential consumers to retrocommission their homes.	DOE, Utilities

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G.20 Intelligent Controls and Diagnostic Technology Options

G.21 Central A/C and Heat Pump Fault Detection and Diagnostics

Brief Description	Fault detection and diagnostic (FDD) systems alert homeowners of common problems associated with residential split-system air conditioners and heat pumps. By identifying performance deviation and determining its cause, directed maintenance can restore the equipment to peak efficiency.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.40 Quads/year	Emerging	Medium

Table G.5.1-1 summarizes central A/C and heat pump fault detection and diagnostics for residential HVAC equipment.

Table G.5.1-1. Summary of the Characteristics of Central A/C and Heat Pump Fault Detection and Diagnostics

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Central air conditioners and heat pumps	
	Fuel Type	Electricity	
	Technical Maturity	Emerging	
	Most Promising Applications	Split-systems	Also packaged units
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency A/C and heat pump equipment	
	Annual Energy Consumption of Baseline Technology	3.06 Quads/yr	
	Applicability to Replacement Market	High	
	Technical Energy Savings Potential	0.40 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	
	Non-Energy Benefits	• Improved comfort • Extended equipment life	
Next Steps for Technology	• Conduct additional 3rd party, laboratory and field testing to verify the energy savings and other benefits from FDD systems over time. • Develop standard fault definitions, thresholds, and communication protocols to increase the interoperability of FDD systems. • Include FDD capabilities in high-efficiency residential HVAC specifications and incentive programs.		

Background

Technology Description

Despite the best efforts of manufactures and installers, undetected faults regularly occur in residential vapor-compression systems, and reduce efficiency over time. For many common faults, energy efficiency decreases before there is a noticeable change in occupant comfort, so the homeowner does not perceive an issue with the HVAC system. Residential fault detection and diagnostic (FDD) systems have been developed to alert homeowners and technicians when an air conditioner or heat pump either fails or experiences a drop in efficiency. After the system relays the presence of a fault, the equipment can be serviced to maintain efficient performance. While their capabilities may vary, FDD for central air conditioners and heat pumps usually can detect several common faults: improper refrigerant charge, compressor malfunction, heat-exchanger fouling, liquid-line restrictions, compressor or valve leakages, or non-condensable gases in the refrigerant. Each of these faults erodes the performance and efficiency of residential HVAC systems, and can also lead to premature equipment failure if left unchecked.

In an FDD system, pressure and temperature sensors placed in key locations provide data to a microprocessor that then compares system parameters against a predictive model to determine if a fault has occurred. Once the unit reaches steady-state operation, the various sensors measure conditions and transmit data to a central processor for analysis. If the difference between measured conditions and a reference exceeds a specified threshold, then the system signals a fault. Once the system determines a fault has occurs, the FDD system then follows an algorithm to diagnose the fault based on the status of the measured conditions. After determining whether a parameter has increased, decreased, or remained the same, this algorithm compares these changes to a predetermined checklist of characteristics corresponding to each measured fault. If the sensor information matches with the predetermined fault characteristics, the system diagnoses the cause of the fault and sends a signal to the homeowner or technician.

Table G.5.1-2 provides a list of common environmental and system parameters measured by FDD sensors. Figure G.5.1-1 provides an example of sensor placement for a split-system heat pump in cooling mode.

Table G.21-2. Commonly Measured Variables in Split-System FDD (Payne et al. 2010)

Variable Type	Component/Placement	Variable
Independent	Outdoor Ambient	Dry-bulb temperature
	Indoor Ambient	Dry-bulb temperature Dew-point temperature
Dependent	Evaporator	Exit saturation temperature Superheat Air temperature drop
	Condenser	Inlet saturation temperature Air temperature rise
	Liquid Line	Subcooling Temperature drop
	Compressor	Discharge wall temperature

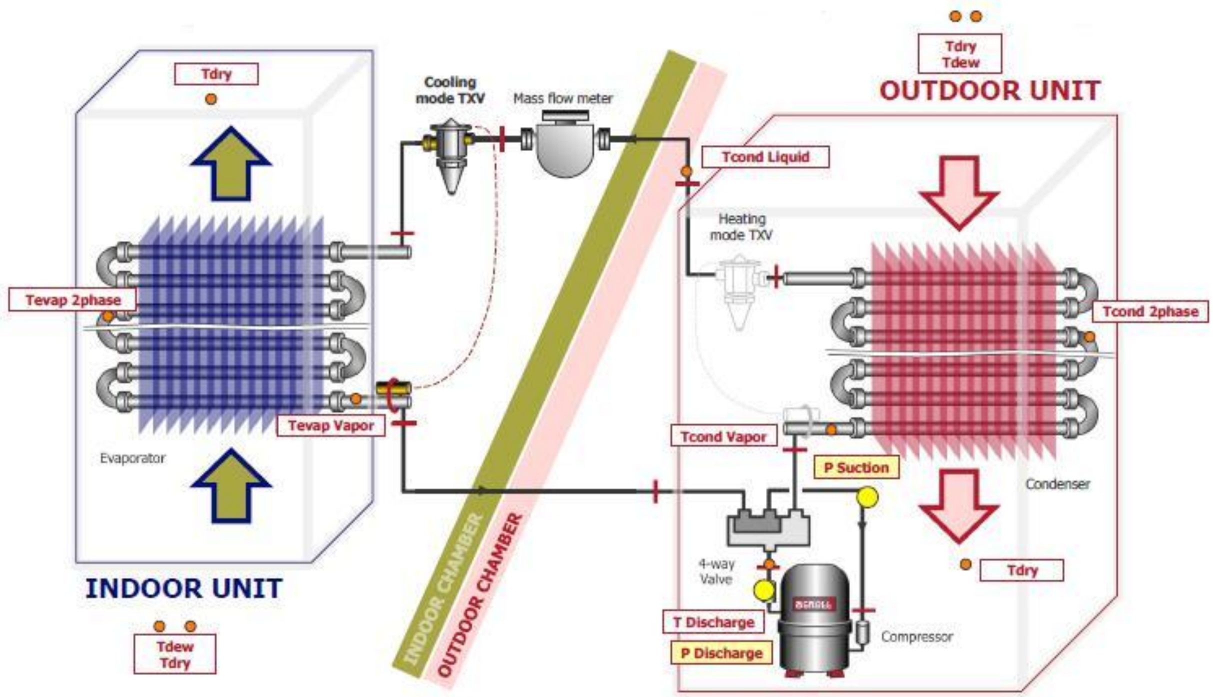

Figure G.21-1. Example Split-System with Embedded Sensors

Source: Payne et al. (2010)

Technical Maturity and Current Developmental Status

This is an emerging technology with limited availability in the U.S. market today. Companies such as Field Diagnostics, Inc. offer FDD tools and sensors that a technician can use to diagnose inefficient performance in the field. One major issue with this current FDD approach is that the technician measures performance for a limited amount of time, which may not represent the unit operations accurately. FDD systems with embedded sensors collect data over the lifetime of equipment and in various environmental conditions to provide much better FDD capabilities.

Much of the current work in this area by both manufacturers and service providers focuses on packaged rooftop units. Commercial products are coming to market with FDD capabilities to meet California Title 24 conservation credits or the DOE's Commercial Building Energy Alliance (CBEA) High-Performance RTU Specification. If successful, manufacturers could apply the same practices to residential equipment.

Barriers to Market Adoption

FDD systems are valuable only if used appropriately. Once a unit provides an alarm for maintenance, it is up to the homeowner to contact a technician to fix the problem. The FDD system may be able to signal the technician directly over the internet, but this feature is unavailable at this time. Occupants may be reticent to contact technicians when a fault occurs because of a lack of familiarity with their HVAC system. In addition to this, variations in equipment usage and the random nature of faults make it difficult to project energy savings and economics for a particular installation. Additionally, if equipment is not installed correctly, the FDD system can produce false alarms that contribute to unnecessary time and expense for both the homeowner and technician, reducing the effectiveness and user acceptance of the FDD system.

Energy Efficiency Advantages

FDD systems recognize when there is a drop in system efficiency and alerts homeowners and technicians to make the necessary repairs. FDD does not automatically fix problems, but quickly points the service technician to the probable cause of the performance drop. FDD does not take the place of regular maintenance, but will track the efficiency of certain key components and the overall system.

Energy Savings Potential

Potential Market and Replacement Applications

For most residential systems, FDD capabilities could be included in high-efficiency replacement equipment. Although FDD principles could be applied to many types of residential HVAC equipment, manufacturers will most likely provide FDD capabilities for split-system air conditioners and heat pumps first because of the prevalence of documented faults and their high number of shipments.

Energy Savings

Although researchers have modeled common faults and verified in the laboratory their efficiency and performance impacts, limited data are available to confirm the benefits of FDD systems in the field.

Lstiburek and Pettit (2010) summarized a number of presentations on residential FDD development that revealed a 20-30% drop in system efficiency from common faults.

Yoon et al. (2010) conducted experiments on a residential heat pump to determine the performance degradation in the presence of common faults. When they tested their system with common faults, COP dropped by more than 10%.

We chose a unit energy savings of 13% based on the assumptions that an FDD system would maintain equipment efficiency 15% better than conventional methods of seasonal maintenance. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.40 Quads of electricity per year.

Cost and Complexity

With the overall price of sensors and microprocessors dropping, factory-installed FDD systems will have nominal cost for parts and only require software development for a manufacturer. Once fully developed, FDD systems should have an attractive payback because of the energy savings, and decreased number of service calls over the life of the equipment.

Lstiburek and Pettit (2010) estimated the cost to manufacturers for residential FDD to be around $70, but this would vary with the type and sensitivity of the sensors used.

Peak-Demand Reduction and Other Non-Energy Benefits

For cooling systems, maintaining high efficiency through FDD and maintenance can reduce peak reduction, generally in proportion to the reduction in energy consumption. By providing maintenance when there is a slight malfunction reduces the chance for a widespread failure and costly replacement. Equipment that operates at its designed performance level will often provide better occupant comfort.

Next Steps for Technology Development

Table G.5.1-3 presents the potential next steps to bring central A/C and heat pump FDD to wider acceptance and achieve significant energy savings in the U.S.

Table G.21-3. Recommended Next Steps for the Development of Central A/C and Heat Pump Fault Detection and Diagnostics

Initiatives	Lead Organization(s)
Conduct additional 3rd-party laboratory and field testing to verify the energy savings and other benefits from FDD systems over time.	DOE, Academic Institutions, Industry Organizations
Develop standard fault definitions, thresholds, and communication protocols to increase the interoperability of FDD systems.	DOE, Industry Organizations, Manufacturers
Include FDD capabilities in high-efficiency residential HVAC specifications and incentive programs.	DOE, Utilities

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G.22 Home Energy Management System

Brief Description	Home EMS employ various energy management and information tools to promote energy savings via home occupant education and feedback.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.37 Quads/year	Emerging	High

Table G.5.2-1 summarizes home energy management systems (EMS) for residential HVAC equipment.

Table G.5.2-1. Summary of the Characteristics of Home Energy Management Systems

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	All HVAC	
	Fuel Type	All	
	Technical Maturity	Emerging	
	Most Promising Applications	HVAC Controls	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency HVAC equipment	
	Annual Energy Consumption of Baseline Technology	3.70 Quads	
	Applicability to Replacement Market	Medium	Homes with broadband access HEMS work with homes that have broadband internet access
	Technical Energy Savings Potential	0.37 Quads	
Other Benefits	**Potential for Peak-Demand Reduction**	High	
	Non-Energy Benefits	• Remote monitoring • Improved energy education • Security system integration	
Next Steps for Technology	• Create a complete home EMS solution for residential applications. • Perform residential case studies and quantify HVAC and whole-home energy savings of an EMS system.		

Background

Technology Description

Many residential consumers do not understand well their energy-consumption trends or how to save energy. Typically, consumers receive energy information primarily through their energy bills; however, the information contained in energy bills is often limited and difficult for consumers to understand. Also, the information comes long after the consumption has occurred. Better and timelier information may help consumers reduce consumption.

In a report for the United Kingdom Department of Environment, Food and Rural Affairs, Sarah Darby (2006) discusses the importance of feedback in energy savings. "…clear feedback is a necessary element in learning how to control fuel use more effectively… and that instantaneous direct feedback in combination with frequent, accurate billing (a form of indirect feedback) is needed as a basis for sustained demand reduction." Darby based her discussion on literature review of studies and trials conducted from the late 1970s through the late 2000s.

Home EMS improve the flow of home energy information to the consumer. Home EMS employ various energy management and information tools that communicate to a central hub. Home EMS provides opportunity for HVAC management, but also manages other home energy systems, such as appliances and lighting. Some HVAC components of home EMS include:

- Energy information: Usable, near real-time data for consumers about their energy consumption. Energy management systems, such as the Intel Home Energy Management System or GE nucleus™, can provide consumption data on each appliance in a home using 'smart' plugs that communicate wirelessly with the main server.
- Remote monitoring: Updates consumers on the status of major energy-consuming components of their home. Home EMS can notify the user of when regular maintenance is required or when a critical component is malfunctioning or not running properly.
- Savings identification/promotion: home EMS can identify appliances using more energy than necessary and recommend ways to reduce energy consumption. Home EMS can also adjust set points for the HVAC system when consumers leave the home and resume normal operation upon their return (or be controlled via phone applications).
- Time-of-use savings (when time-of-use rate structures are available): home EMS can show consumers what times are more expensive to run HVAC equipment, reducing peak demand and saving consumers money.
- Home EMS can interact with learning thermostats to provide homeowners with detailed feedback about temperature settings. See Learning Thermostats for further discussion.

Technical Maturity and Current Development Status

Home EMS are an emerging technology, with limited residential availability in the United States. EMS are practiced in commercial buildings where the technology is commercially available. Some major companies, such as Intel and GE, have developed prototypes for demonstration, but they have not commercialized the systems. One company, Control4, has an energy dashboard, a precursor to a home EMS but with less functions, on the market (the EMS 100), according to

Katie Fehrenbacher, in an article for Gigaom (a technology news site) (Fehrenbacher 2009). They claim the EMS 10 can balance operation of home systems (HVAC, lighting, security, etc.) while responding to time-of-use price signals from the utility.

Barriers to Market Adoption

Privacy concerns could limit market adoption of home EMS; some consumers may not want utilities to have access to their HVAC and other home systems. Also, there is the potential for HEMS to be hacked.

Energy Efficiency Advantages

Home EMS save energy by improving the control and user visibility of the home-energy consumption, including HVAC energy. Home energy management systems can:

- Identify areas where the consumer could reduce energy consumption
- Monitor HVAC equipment for maintenance needs and malfunction
- Recommend new energy-efficient products to replace older equipment
- Encourage shifting discretionary loads to off-peak times by communicating utility price signals.

Energy Savings Potential

Potential Market and Replacement Applications

Home EMS are suitable for U.S. homes in all climates and regions; however, HEMS are limited to residential consumers with broadband access (and broadband subscription). Home energy management systems can be installed in new construction, or added to existing homes.

Energy Savings

Darby (2006) claims direct feedback, provided by HEMS, can save 5-15% of whole–home energy consumption based on literature review.

Granderson et al. (2009), in an LBNL study of commercial and educational buildings, found 18-30% energy reduction in case studies at UC Merced, Sysco, and UC Berkeley. These energy reductions included lighting reductions.

We chose a unit energy savings of 7.5% based on the assumptions that …. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.20 Quads of electricity per year and 0.16 Quads of natural gas per year.

Cost and Complexity

Our literature search did not identify cost estimates for residential HEMS applications. Current prices for computer systems with similar processing power suggests the price for a home energy management system may be about $1000-$2000 installed.

Peak-Demand Reduction and Other Non-Energy Benefits

Granderson et al. (2009)), in an LBNL study of commercial and educational buildings, found a 35% peak-demand reduction (during a single observation) during a case study at Sysco's Northern California warehouse.

Home EMS can control many systems in the home, including security systems, lighting systems, room-to-room communication, phone systems, and appliance controls. HEMS can also be integrated with utility companies to allow for demand response and leverage time-of-use pricing. Home EMS can use phone applications and web-based controls to allow remote access to all home systems controlled by the home EMS.

Next Steps for Technology Development

Home EMS have been demonstrated by two large corporations (Intel, GE). Katie Fehrenbacher (2009), notes 10 energy dashboards available on the market, which are a precursor to home EMS. However, no complete systems are available on the market. In a Smart Grid News commentary (2010), the author notes that a homeowner would have to put together a home energy management system using components from various companies. Dashboards (which offer some of the features of HEMS) are sporadically available in the market.

Table G.5.2-2 presents the potential next steps to bring home energy management systems to gain wider acceptance and achieve significant energy savings in the U.S.

Table G.22-2. Recommended Next Steps for the Development of Home Energy Management Systems

Initiatives	Lead Organization(s)
Perform residential case studies and quantify HVAC and whole-home energy savings of an EMS system.	DOE, Manufacturers, Utilities
Create a complete home EMS solution for residential applications.	Manufacturers

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G.23 Learning Thermostats

Brief Description	The learning thermostat improves upon a conventional programmable thermostat by automating temperature-schedule creation based on initial user inputs and occupancy habits.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.74 Quads/year	Emerging	Medium

Table G.5.3-1 presents a summary overview of learning thermostats for residential HVAC equipment.

Table G.5.3-1. Summary of the Characteristics of Learning Thermostats

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	All central heating and cooling systems	
	Fuel Type	Various	Thermostat runs off electricity; can control gas, oil, electric and other fuel HVAC systems.
	Technical Maturity	Emerging	Products became available on the market in 2011. Availability limited.
	Most Promising Applications	Residential HVAC controls	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency central HVAC equipment	
	Annual Energy Consumption of Baseline Technology	7.39 Quads	
	Applicability to Replacement Market	High	New and existing HVAC systems Learning thermostats could supplement all central HVAC installations.
	Technical Energy Savings Potential	0.74 Quads	
Other Benefits	**Potential for Peak-Demand Reduction**	High	The learning thermostat could include demand response or promote behavior change (with on-screen display). This will require price signal from utility.
	Non-Energy Benefits	• Remote access to thermostat to alter temperature when not at home	
Next Steps for Technology	• Address issues with occupancy sensing enable communication among multiple thermostats, and scheduling • Study the user acceptance, reliability and effectiveness of learning thermostats		

Background

Technology Description

Conventional programmable thermostats control HVAC systems based on a temperature set-point schedule input by the user. However, T. Peffer et al. (2011) claim only 30% of consumers own programmable thermostats and half of programmable thermostat users do not program their thermostats to adjust temperature during unoccupied times. Standard programmable thermostats can be complex, proving difficult for the standard user to operate. A study by Meier et al. (2011) found most occupants manually operated programmable thermostats and 90% rarely or never set a weekly schedule.

The learning thermostat improves upon the standard programmable thermostat by determining the desired schedule automatically. Instead of setting a schedule at setup like a programmable thermostat, the user begins setting the learning thermostat as if it were a manual thermostat, changing the temperature whenever a new temperature is desired. The learning thermostat begins creating a schedule from the user-input temperatures and occupancy habits (which the device monitors via an occupancy sensor).

Learning thermostats create a schedule using proprietary algorithms to optimize temperature settings (i.e., minimize space-conditioning loads during unoccupied periods, when comfort is not a consideration). If a user repeatedly changes the temperature set point, the learning thermostat alters the schedule to reflect the new user preferences. Large houses or houses with zonal controls require multiple thermostats for proper function.

Technical Maturity and Current Developmental Status

This technology became available in the U.S. in 2011. The technology is being sold through a few big-box retailers (e.g., Amazon, Best Buy), but supply and market penetration is limited.

Learning thermostats are undergoing software updates to improve integration with HVAC systems. Some users are experiencing software issues, including, communication between multiple thermostats, incorrect occupancy sensing, and incorrect scheduling, according to Aaron (2012), a blogger for WiredPrairie .

Barriers to Market Adoption

The learning thermostat, currently priced between $200 and $400, is more expensive than conventional programmable thermostats, which are typically between $30 and $50. Most homes will require multiple thermostats to detect occupancy. Additionally, false occupancy readings may occur because of pets or motion through windows. Privacy and security may be a concern for some consumers because of third-party access to personal data and occupancy information.

Energy Efficiency Advantages

Darby (2006) claims feedback of energy information can reduce annual HVAC energy consumption 5-15%. The learning thermostat collects data on energy consumed by the HVAC system, weather conditions, and user information (occupancy, user inputs) and provides reports via web portal and/or smart-phone application. The thermostat lets the user know when she saves energy compared to her home's baseline via the thermostat's hardware interface.

The learning thermostat may also have HVAC system monitoring of HVAC systems. The Ecobee thermostat detects issues with the home's HVAC system and can notify the user and possibly a contractor of any performance problems and upcoming maintenance requirements.

Energy Savings Potential

Potential Market and Replacement Applications

Learning thermostats are applicable in all climate regions and can be installed as replacements or in new constructions. They will work in single-family or multi-family applications; however, they may save less energy in multi-family depending on building configuration and occupants' schedules. Learning thermostats provide the most benefit to users who would not otherwise use programmable thermostats effectively.

The learning thermostat is an emerging technology with availability in the United States market. Two products, the Nest thermostat and the Ecobee thermostat, can be found at Best Buy and Amazon.com, respectively.

Energy Savings

G. Gao et al. (2009) claim a self-programming (learning) thermostat can reduce heating and cooling demand by 15%.

Nest Labs (2011) alleges the Nest Learning Thermostat can reduce energy consumption 5-30% by creating a schedule for the user.

Ecobee (2012) estimates their thermostat saves 20% of heating and cooling energy consumption.

We estimate a unit energy savings of 10% because learning thermostat energy savings are depending upon some user interaction with the thermostat; however, the concept of a 'learning thermostat' promotes the notion of the thermostat adjusting to the consumer. Therefore, we estimate energy savings are on the lower end of the range from literature. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.41 Quads of electricity per year and 0.33 Quads of natural gas per year.

Cost and Complexity

Nest Labs sells its Nest Learning Thermostat for $249 according to the Nest Store (2012). The Ecobee Smart Internet Thermostat sells for $292 according to Amazon.com (2012).

Ecobee (Ecobee 2012) and Nest Labs (Nest 2011) claim most users can install their products without assistance. Professional installation of the thermostat typically costs an additional $100.

The learning thermostat uses complex, protected algorithms to learn an occupant's preferences. Learning thermostat companies will refine the algorithms to better suit occupant preferences, but this will require years of trials by end users.

Peak-Demand Reduction and Other Non-Energy Benefits

Learning thermostats contain Zigbee hardware that could support demand-response controls. (Seidle 2011). Both current manufacturers include hardware in their learning thermostats for future innovation in grid technology. In the future, software updates could allow the thermostats to interact with utilities.

Web applications could allow for remote access to the thermostats using a smart phone or internet connection. This would allow occupants or utilities to change temperature settings from outside the house to respond to a utility need to lower demand.

Next Steps for Technology Development

The learning algorithms of the learning thermostats may need additional development as some consumers, such as Aaron on WiredPrairie (2012), have noted issues with the Nest software.

A study of learning thermostats to demonstrate energy savings would better define the energy savings potential. Current estimates of energy savings from learning thermostats are either manufacturer-created ((Nest 2011), (Ecobee 2012)), theoretical (G. Gao et al. 2009), or survey-based (T. Peffer et al. 2011).

Table G.5.3-2 presents the potential next steps for learning thermostats to gain greater market attention and acceptance.

Table G.23-2. Recommended Next Steps for the Development of Learning Thermostats

Initiatives	Lead Organization(s)
Conduct long-term study of learning thermostats to demonstrate energy savings	DOE, Utilities, Manufacturers
Study the user acceptance, reliability and effectiveness of learning thermostats	DOE, Utilities
Address issues with occupancy sensing enable communication among multiple thermostats, and scheduling	Manufacturers

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G.24 Smart Ceiling-Fan Controls

Brief Description	Operating a ceiling fan allows the thermostat to be set 2-4 °F higher during the cooling season while maintaining similar comfort levels for occupants. In combination with raised temperatures, smart ceiling-fan controls using occupancy sensors operate only when a room is occupied, reducing ceiling-fan energy consumption.	
Technical Energy Savings Potential	**Technical Maturity**	**Cost/Complexity**
0.02 Quads/year	Emerging	Medium

Table G.5.4-1 summarizes smart ceiling-fan controls for residential HVAC equipment.

Table G.5.4-1. Summary of the Characteristics of Smart Ceiling-Fan Controls

Attribute		Value	Comments
Technology Characteristics	**Equipment Type to which Technology is Most Applicable**	Central cooling equipment	
	Fuel Type	Electricity	
	Technical Maturity	Emerging	
	Most Promising Applications	Southeastern U.S.	
Energy Savings Estimate	**Baseline Technology (Current Technology that would be Displaced)**	Standard-efficiency central HVAC equipment	
	Annual Energy Consumption of Baseline Technology	0.20 Quads/yr	Central cooling systems in the Hot/Humid climate region.
	Applicability to Replacement Market	Medium	Included in replacement models or could be retrofit onto existing fans.
	Technical Energy Savings Potential	0.02 Quads/yr	
Other Benefits	**Potential for Peak-Demand Reduction**	Medium	
	Non-Energy Benefits	• Connectivity with home energy networks	
Next Steps for Technology	• Investigate the benefits of smart ceiling-fan controls through both laboratory and field testing to verify energy savings and end-user acceptance. • Work with EPA to incorporate smart ceiling-fan controls with occupancy sensors into the ENERGY STAR high-efficiency ceiling-fan specification.		

Background

Technology Description

Ceiling fans direct air downward onto occupants who feel cooler (due to evaporation of perspiration) permitting higher set-point temperatures for cooling systems, resulting in energy savings. The moving air from a ceiling fan can decrease the apparent temperature of a room by 4 ˚F (KSU 2005). Improving ceiling-fan controls through the use of occupancy sensors to control fan operation and adjust thermostat settings can result in significant energy savings without a noticeable change in comfort.

The key component of smart ceiling fans is the occupancy sensor, shown in Figure G.5.4-1. An infrared motion sensor located on the central hub of the fan offers an unobstructed view of the room below. Placing a Fresnel lens over the motion sensor greatly increases the capabilities of the sensor by capturing movement that is far away or at a low visual angle from the fan. Once the sensor detects movement in a room, the controls activate the fan, and provide cooling to the occupants. If the sensor does not detect movement after a period of time, the ceiling fan shuts off. The smart ceiling fan can suspend its control sequence under low-light or dark conditions, maintaining its current state. This is necessary to keep the fan operating when occupants are sleeping, and subsequently are not moving.

Figure G.24-1. Occupancy Sensor for Smart Ceiling Fan with Fresnel Lens

Source: Parker et al. (1999)

Technical Maturity and Current Developmental Status

This technology is not commercially available, and there are a few product development issues to be resolved. The GossamerWind ceiling fan developed in the 1990s at the Florida Solar

Energy Center contained numerous high-efficiency features, including occupancy controls (Parker et. al., 1999). The Home Depot brand Hampton Bay acquired the GossamerWind technology and markets products under the “Windward” name. The current controls do not include an occupancy sensor, but, instead, a temperature sensor turns on the fan when the room temperature rises above a setpoint.

Barriers to Market Adoption

This technology would be more easily implemented homes (such as apartments) with only a few rooms. Many single-family homes would need fans placed in each of the major rooms of the home. Because most homeowners would not install smart ceiling fans where fan wiring does not already exist, the additional cost of installation, or concerns about room aesthetics, may outweigh any potential energy savings. Nevertheless, ceiling fans are prevalent in the Southeast U.S. with residents using fans throughout their home (Parker 2012). In these instances, smart ceiling fans would replace conventional models at the end of their operating life, or controls could be retrofit onto existing fans.

Energy Efficiency Advantages

Ceiling fans are a low-energy-intensity way to supplement space cooling. The thermostat can be set at a higher thermostat temperature, and ceiling fans automatically turn on when someone is present in the room. Offsetting the energy consumption of the main cooling system with additional fan usage provides a net energy savings while maintaining occupant comfort.

Energy Savings Potential

Potential Market and Replacement Applications

This technology could be retrofit into existing homes that already have ceiling fans. While rooms with high ceilings can use ceiling fans for destratification during the heating season, most residential applications would not be suitable for winter use. A ceiling fan operating in the winter, even directed upward, would feel cold to occupants in rooms under 12-15 ft. high. This technology would be most applicable for homes in the hot/humid climate region where residential ceiling fans are common.

Energy Savings

James et al. (1996) investigated ceiling fan usage to supplement air-conditioning systems in Florida. They determined that a 2 ˚F rise in a home’s temperature would correspond to a 14% net decrease in cooling-season energy use once accounting for fan motor consumption and heat addition. While energy savings from this study follow a linear curve between 0.5-2 ˚F, it is unknown what savings could be achieved at 4 degF.

KSU (2005) states that each degree F that the thermostat is raised reduces cooling energy consumption by 3-4%. So, a 4˚F rise in home temperature could correspond to a 12-16% decrease in cooling energy use.

Ceiling fans will not replace a central cooling system except in a very limited range of temperate climates, but improves the efficiency of homes already using ceiling fans to augment central cooling. Energy savings are dependent on the thermostat increase allowed by the ceiling fan, the efficiency of the fan motor and the amount of time that the occupancy controls turn off the fan..

We estimated a unit energy savings of 10% based on the assumptions that a home would typically raise their thermostat by 2-4 ˚F and have smart ceiling fans with standard-efficiency motors. Although this technology would be applicable in any location using central cooling, we estimate energy savings based on a medium replacement potential for the hot/humid climate region where ceiling fans are more prevalent. Based on an analysis of its potential impact on HVAC systems in the U.S., this technology would save 0.02 Quads of electricity per year.

Cost and Complexity

The price for ceiling fans varies widely based on the fan design, component efficiency, and more prominently by aesthetics. The incremental cost for smart ceiling fans is estimated $30-40 over conventional models (Parker 2012). Because of this, the incremental cost for high-efficiency features may be absorbed within other purchasing considerations.

Peak-Demand Reduction and Other Non-Energy Benefits

Smart ceiling fans have a medium potential for peak-demand reductions associated with the reduction in cooling-season HVAC energy, but would not be directly proportional because of the fan consumption use. While not currently offered by manufacturers, the motion sensor could provide occupancy information for use by a home energy network.

Next Steps for Technology Development

Table G.5.4-2 presents the potential next steps to bring smart ceiling-fan controls to wider acceptance and achieve significant energy savings in the U.S.

Table G.24-2. Recommended Next Steps for the Development of Smart Ceiling-Fan Controls

Initiatives	Lead Organization(s)
Investigate the benefits of smart ceiling-fan controls through both laboratory and field testing to verify energy savings and end-user acceptance.	DOE, Academic Institutions, Utilities
Work with EPA to incorporate smart ceiling- fan controls with occupancy sensors into the ENERGYSTAR high-efficiency ceiling-fan specification.	DOE

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