U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

BUILDING TECHNOLOGIES OFFICE

Research & Development Roadmap for Emerging HVAC Technologies

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October 2014

Prepared by Navigant Consulting, Inc.

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Preface

The Department of Energy's (DOE) Building Technology Office (BTO), a part of the Office of Energy Efficiency and Renewable Energy (EERE) engaged Navigant Consulting to develop this research and development (R&D) roadmap for heating, ventilation, and air conditioning (HVAC) technologies. The initiatives identified in this report are Navigant's recommendations to BTO for pursuing in an effort to achieve DOE's energy efficiency goals. Inclusion in this roadmap does not guarantee funding; HVAC initiatives must be evaluated in the context of all potential activities that BTO could undertake to achieve their goals.

BTO also manages the residential appliance and commercial equipment standards program; however these activities are separate. To maintain the separation between the emerging technologies activities and the appliances standards activities, and to prevent undesirable interaction between the two, this roadmap does not cover any details of the following topics (general discussion of challenges, barriers, or needs in these areas may be covered as appropriate):

» Test procedures

» Energy efficiency descriptors

» Efficiency standards levels.

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

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Acknowledgements

We would like to thank the individuals who provided valuable input to this roadmap, including:

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Robert Wilkins	Danfoss
Jing Zheng	Coca-Cola Company
Tony Ziegler	Laboratory & Biosafety System Inc.

List of Acronyms

A/C	Air Conditioner or Air Conditioning
ACCA	Air Conditioning Contractors of America
AEO	Annual Energy Outlook
AFUE	Annual Fuel Utilization Efficiency
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
API	Application Programming Interface
ARPA-e	Advanced Research Projects Agency-Energy
AS-IHP	Air-Source Integrated Heat Pump
BTO	Building Technologies Office
CBECS	Commercial Buildings Energy Consumption Survey
CBERD	U.S.-India Joint Center for Building Energy Research and Development
CCE	Cost of Conserved Energy
CCHP	Cold-Climate Heat Pump
CERC	U.S.-China Clean Energy Research Center
CFC	Chlorofluorocarbon
CHP	Combined Heat and Power
COP	Coefficient of Performance
CRADA	Cooperative Research and Development Agreements
DCV	Demand-Controlled Ventilation
DHC	District Heating and Cooling
DOAS	Dedicated Outdoor Air System
DOE	Department of Energy
EER	Energy Efficiency Ratio
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Agency
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERV	Energy Recovery Ventilator
EU	European Union
FDD	Fault Detection and Diagnostics
FEMP	Federal Energy Management Program
FOA	Funding Opportunity Announcements
GHP	Geothermal or Ground-Source Heat Pump
GS-IHP	Ground-Source Integrated Heat Pump
GWP	Global Warming Potential
HP	Heat Pump
HPWH	Heat Pump Water Heater
HSPF	Heating Season Performance Factor
HVAC	Heating, Ventilation, and Air Conditioning
HVAC&R	Heating, Ventilation, Air Conditioning, and Refrigeration

IAQ	Indoor Air Quality
IEER	Integrated Energy Efficiency Ratio
IEQ	Indoor Environmental Quality
IHP	Integrated Heat Pump
IPOS	Image Processing Occupancy Sensor
LBNL	Lawrence Berkeley National Laboratory
NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
O&M	Operations and Maintenance
ORNL	Oak Ridge National Laboratory
PCM	Phase-Change Material
PNNL	Pacific Northwest National Laboratory
PTAC	Packaged Terminal Air Conditioner
P-Tool	Prioritization Tool
PV	Photovoltaic
PV/T	Photovoltaic and Thermal
Quad	Quadrillion (10^{15}) Btu
R&D	Research and Development
RECS	Residential Energy Consumption Survey
RTU	Rooftop Unit
SEER	Seasonal Energy Efficiency Ratio
SMDS	Smart Monitoring and Diagnostics
SNL	Sandia National Laboratory
SSLC	Separate Sensible and Latent Cooling
STES	Seasonal Thermal Energy Storage
ToU	Time of Use
TRL	Technology Readiness Level
VFD	Variable-Frequency Drive
VHP	Vuilleumier Heat Pump
VOC	Volatile Organic Compounds

Executive Summary

The U.S. Department of Energy's (DOE) Building Technologies Office (BTO) within the Office of Energy Efficiency and Renewable Energy (EERE) works with researchers and industry partners to develop and deploy technologies that can substantially reduce energy consumption in residential and commercial buildings. BTO aims to reduce building-related primary energy consumption by 50% by the year 2030, relative to 2010 consumption. Specifically for heating, ventilation, and air conditioning (HVAC), BTO identified primary energy savings targets of 12% by 2020 and 24% by 2030.

This roadmap aims to advance BTO's energy savings goals by identifying research and development (R&D) initiatives for high efficiency HVAC technologies. Their focus is on innovative initiatives that accelerate development of technologies. This includes those initiatives that produce near-term improvements as well as those that advance development of next-generation or transformational technologies.

DOE retained Navigant Consulting Inc. (hereafter, "Navigant") to identify and characterize high-priority research and development (R&D) activities for BTO to pursue. This roadmap covers all commercial and residential HVAC technologies, including related systems, such as controls, distribution systems, and operations and maintenance.

To gather input for this roadmap, we conducted one-on-one interviews with industry leaders and held a stakeholder forum on June 17, 2014, generously hosted by ASHRAE at their headquarters in Atlanta, GA. Key themes arose from stakeholder discussion, including:

- **Building in tolerance for system misapplication**, e.g., ability to accommodate for oversizing without hurting performance
- **Recognize that each building is a unique system** and they can vary widely in their operating characteristics and requirements
- **Envision what retrofits look like in 2050**, as such awareness can help improve HVAC system design and reduce maintenance and replacement costs in the future.
- **Emphasize peak demand mitigation**, which will provide system-wide reliability environmental benefits as well as customer cost benefits
- **Optimize components for alternative refrigerant systems** given that the transition to low global-warming-potential (GWP) refrigerants will be a prominent driver of technological change.

In all, stakeholders provided nearly 100 unique ideas for initiatives. We carefully characterized the full set of initiatives and evaluated them using multivariate analysis with both qualitative and quantitative metrics. Table ES-1 and Table ES-2 show the resulting high priority initiatives for direct-impact technologies and enabling technologies, respectively. Direct-impact initiatives address specific technical innovations to provide energy savings, while enabling initiatives indirectly aid improvements in energy efficiency via supplementrary technologies, processes, or knowledge advances.

Table ES-1: Priority Direct-Impact HVAC R&D Initiatives

Topic Area	Initiative/Activity
Renewables & Storage	Develop a direct-current (DC)-powered HVAC system to utilize DC power from a solar PV system without inverter losses and facilitate microgrid integration
AC/HP	Develop and evaluate techniques for separate sensible and latent control and quantify the energy savings
AC/HP	Develop techniques to raise heat pump performance (all fuels) at low-ambient temperature; consider elimination of defrost (or frost buildup) and backup heat sources to improve the application of CCHPs
AC/HP	Develop electrochemical compression systems
Renewables & Storage	Develop methods, technologies, and other innovations to easily integrate seasonal energy storage into residential and commercial projects
AC/HP	Investigate new absorption pairs, compact heat exchangers, and other material advances to reduce the cost of absorption systems for res/light commercial

Table ES-2: Priority Enabling HVAC Technology R&D Initiatives

Topic Area	Initiative/Activity
Installation O&M	Collect data and conduct analysis on the pervasiveness and energy impacts of incorrect system commissioning, poor installation, incorrect operation, and improper maintenance of HVAC in all buildings
FDD Controls	Develop and demonstrate an open-source, open-architecture platform that enables smart grid connectivity for demand response, and communication of energy, operational, and financial transactions between HVAC and other building systems
FDD Controls	Develop a low-cost sensor network and control scheme where every surface, critical object, and occupant has a sensor
Tools & Software	Develop standardized methods of built-in data acquisition and data storage for sizing and equipment selection purposes at end of life

The report that follows provides detailed background on current R&D efforts in water heating, discussion of BTO's overall approach to water heating R&D, and clear articulation of the Tier 1 priority initiatives. The report is organized as follows:

1. **Introduction/Background** – objectives, BTO role and current R&D
2. **Roadmap Approach** – R&D roadmap development process steps
3. **Market Overview** – current state of technology and the water heating market
4. **R&D Roadmap** – detailed discussion of priority initiatives, as well as general discussion of themes; Tier 1 (highest-priority) initiative discussion includes discussion of technical and market barriers, timelines and milestones, and stakeholder roles.

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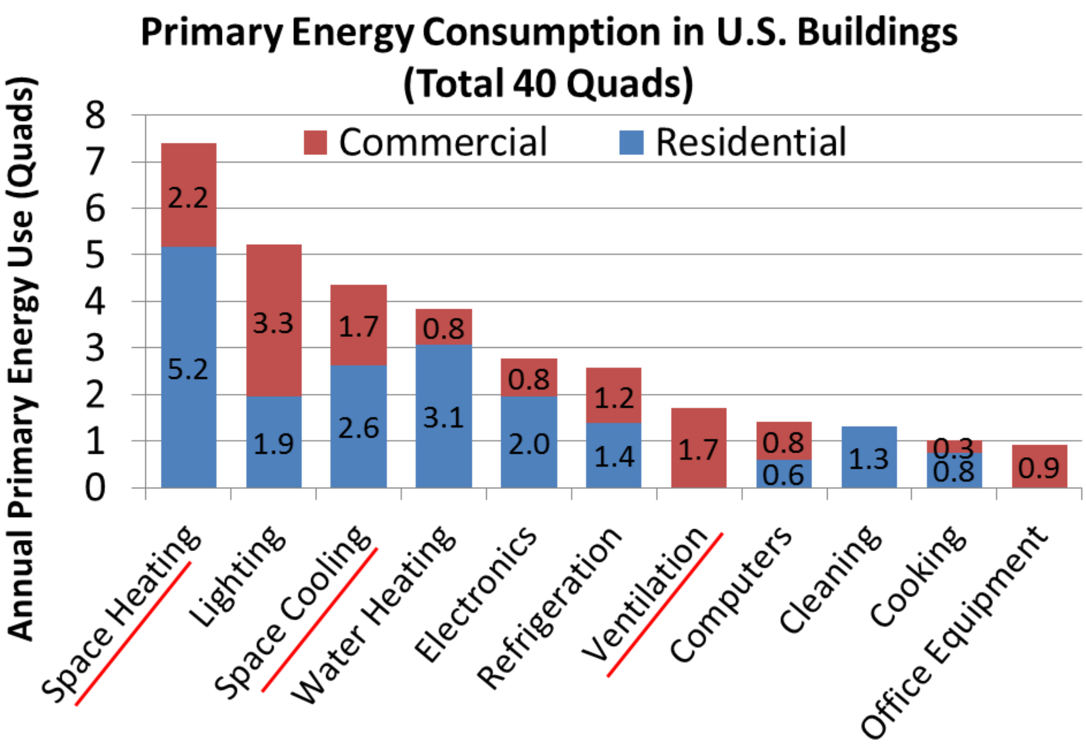
1 Introduction

1.1 Background

The Building Technologies Office (BTO) within the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy works with researchers and industry to develop and deploy technologies that can substantially reduce energy consumption in residential and commercial buildings. BTO aims to reduce building-related energy consumption by 50% by the year 2030, relative to 2010 consumption. Further development of emerging Heating, Ventilation and Air Conditioning (HVAC) technologies has the potential to help BTO achieve this goal.

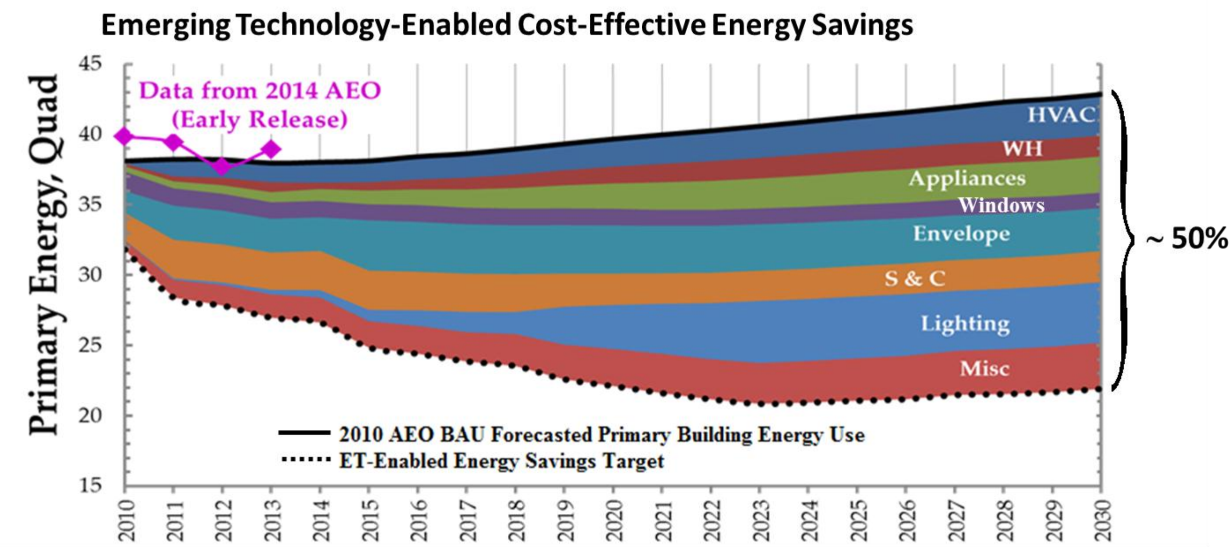
As of 2010, HVAC loads constituted 41% of all building primary energy consumption in the U.S. Figure 1-1 shows the breakdown of primary energy consumption by end use.



Source: 2013 data from BTO Prioritization tool; developed based on 2010 EIA Annual Energy Outlook data

Figure 1-1: Building primary energy consumption by end-use

Figure 1-2 shows BTO's projected energy savings potential relative to the Energy Information Administration's (EIA) Annual Energy Outlook (AEO) projections for total consumption. BTO's 50% target savings goal, a 20 quadrillion (10^{15}) Btu (quad) reduction in primary energy, comes from all building technologies combined; each colored band in the figure represents the savings achievable over time from each end-use. The overlaid data from AEO 2014 (purple line) shows how the projections compare to actual consumption.



Source: Energy Information Administration's (EIA) Annual Energy Outlook (AEO); savings estimates from BTO

Figure 1-2: BTO emerging-technology-enabled energy savings targets

As defined in its Multi-Year Work Plan, BTO's mission is to:

> Develop and promote efficient and affordable, environmentally friendly, technologies, systems, and practices for our nation's residential and commercial buildings that will foster economic prosperity, lower greenhouse gas emissions, and increase national energy security while providing the energy-related services and performance expected from our buildings.[1]

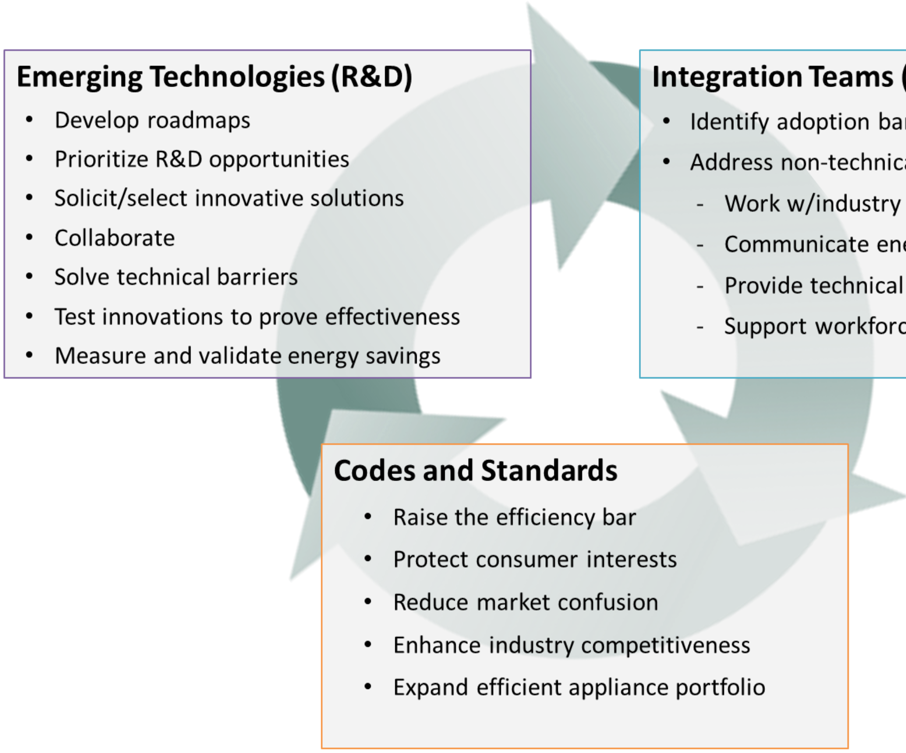
As part of this mission, BTO targets primary energy savings of 24% for HVAC (12% by 2020).[2]

1.2 BTO HVAC Research and Development (R&D) Approach

BTO maintains an integrated approach to accelerating uptake of energy efficient technologies that leverages the three key and distinct portions of the organization: codes and standards, market priming teams, and emerging technologies. Figure 1-3 shows the key functions of each group.

[1] Department of Energy, Office of Energy Efficiency and Renewable Energy. "Building Technologies Program Multi-Year Work Plan 2011–2015." Accessed September 2, 2014: apps1.eere.energy.gov/buildings/publications/pdfs/corporate/myp11.pdf

[2] BTO's target savings general information available at: www1.eere.energy.gov/buildings/technologies/index.html. Specific breakdown by end-use based on slide 3 of a presentation by Pat Phalen, Emerging Technologies program manager, (April 22, 2014). Accessed September 2, 2014: energy.gov/sites/prod/files/2014/05/f15/BTO_PeerReview_ET_Overview_042214.pdf.



Source: BTO Presentation: energy.gov/sites/prod/files/2014/05/f15/HVAC_Overview_Bouza_042314_and_042414.pdf

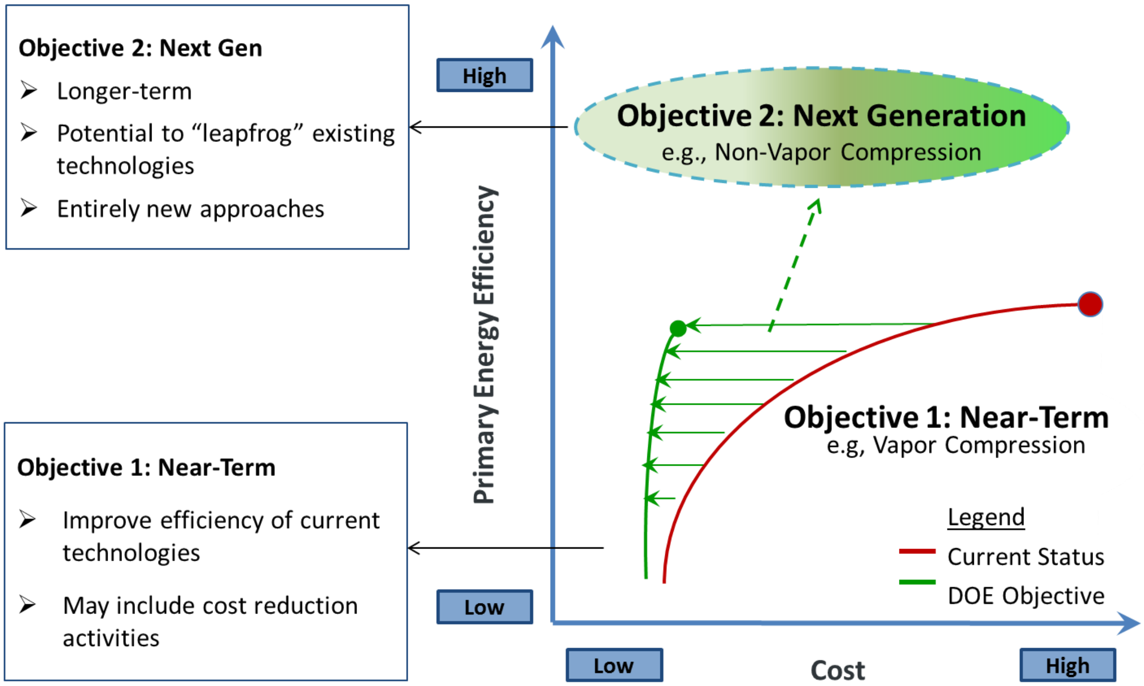
Figure 1-3: BTO overall approach by group function

The emerging technologies group specifically has the goal of developing technologies that save energy and reduce our environmental burden while introducing them in the simplest applications first, for the highest probability of success. BTO maintains a two-pronged approach to help achieve this goal:[3]

1) Accelerate the development of **near term** technologies that have the potential to save significant amount of energy (which may include cost reduction activities)
2) Accelerate the development of the **next generation** of technologies that have the potential of "leapfrogging" existing technologies by pursuing entirely new approaches (including crosscutting efforts).

Figure 1-4 shows how BTO views these objectives relative to cost and efficiency improvements.

[3] Tony Bouza, BTO Presentation: "ET's HVAC, WH and Appliance R&D." (April 24, 2014) Accessed September 15, 2014: energy.gov/sites/prod/files/2014/05/f15/HVAC_Overview_Bouza_042314_and_042414.pdf



Source: Refined from BTO Presentation: energy.gov/sites/prod/files/2014/05/f15/HVAC_Overview_Bouza_042314_and_042414.pdf

Figure 1-4: BTO approach to HVAC R&D

The Emerging Technologies group has identified objectives for their HVAC R&D, including:

- Leverage previous work on less complex technologies, such as water heating; such advances must recognize differences in key energy consumption factors, e.g., water heating is dependent on usage patterns, whereas HVAC is more dependent on envelope, equipment sizing, and floor area.
- Maintain a diverse portfolio of HVAC R&D activities in terms of topic/technology readiness level (TRL), fuel choice, and market.
- Enable consumer choice (without forcing on-site fuel switching).
- Maintain cost effectiveness as a key goal, recognizing that the first commercialized iteration of a product may not ultimately achieve the final target.

In achieving those objectives, BTO sees four leading themes:

- Continued emphasis on integrated systems that enable key cross-cutting benefits
- Primary energy savings focus versus site energy savings
- Consideration of regional and temporal differences in primary energy savings due to electricity generation fuel mix
- Increased importance of regionally-optimized and climate-optimized solutions as additional efficiency gains tend to require such a move.

In understanding what the building energy landscape looks like in 2030, one must consider the impact of some key changes, including:

- **Water scarcity** – higher water costs (and higher energy prices as a result) will become a driving factor in the energy industry; while this primarily impacts the power generation sector, many building technologies have an impact as well.
- **Tightly sealed buildings** – new building techniques and envelope energy savings measures lead to better building envelope sealing, which in turn impacts not only the heating and cooling capacity requirements but also ventilation and humidity control needs.
- **Higher energy costs** – in combination with increasing water prices, consumer can expect increasing energy costs. For example, EIA predicts nearly a 30% increase in the cost of natural gas for residential customers by 2030 (relative to 2012).[4]

To achieve their objectives, BTO expects to continue their use of Funding Opportunity Announcements (FOA) for initiating early-stage work and their use of Cooperative Research and Development Agreements (CRADA) to leverage manufacturer experience in successful technology deployment and commercialization.

The following subsection documents BTO's technology-specific goals for cost and efficiency. The four subsequent subsections summarize selected recent and ongoing BTO R&D activities that are representative of their typical work.

1.2.1 BTO Emerging Technologies Goals in HVAC

BTO identified near-term efficiency and cost targets for six different HVAC technology areas (based on analysis for the P-Tool):

- Multifunction Natural Gas-Driven Heat Pumps – See Figure 1-5
- Air-Source Integrated Heat Pumps – See Figure 1-6
- Advanced Vapor-Compression Technologies – See Figure 1-7
- Non-Vapor-Compression HVAC Systems – See Figure 1-8
- Natural Gas-Driven Heat Pumps – See Figure 1-9
- Cold-Climate Heat Pumps – See Figure 1-10

Each figure shows the efficiency based on primary energy, i.e., primary energy savings or primary seasonal COP. Primary energy additionally accounts for the losses associated with generation/transmission/distribution of electricity for electricity-driven systems so that efficiencies of system using different fuels can be directly compared. The figures show costs based on either Installed Cost Premium per square foot ($/sq.ft.) or Installed Cost per kBtu per hr ($/kBtu/hr), which is relative to the installed cost of a typical baseline model using the same fuel as the target technology.[5] Each of the six technologies is applicable to both residential and commercial applications, except for air-source integrated heat pumps, which BTO targets for use in residential applications only.

[4] Energy Information Administration, Annual Energy Outlook. 2014. Table A3: Energy prices by sector and source. Accessed September 2, 2014: www.eia.gov/forecasts/aeo/pdf/tbla3.pdf.
[5] Baseline assumptions based on BTO analysis for P-Tool, using EIA data as the primary basis.

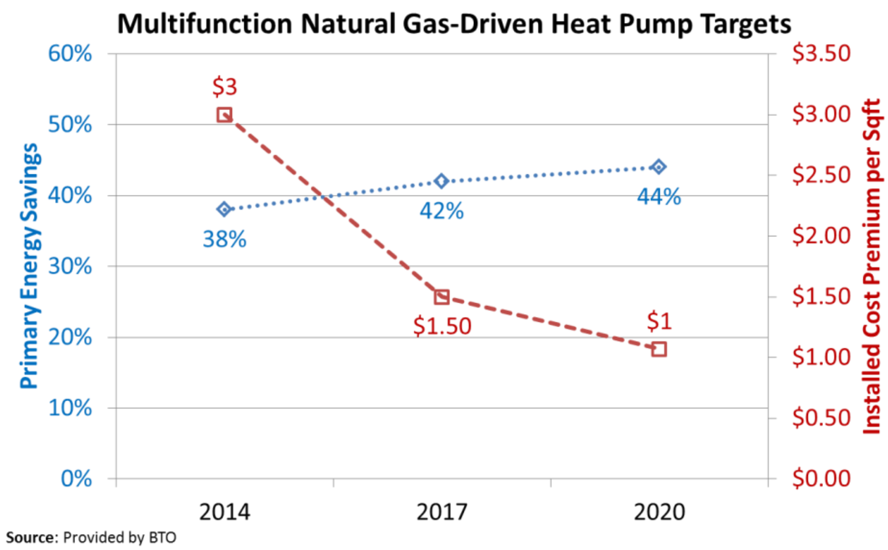


Figure 1-5: Cost and efficiency targets for multifunction natural gas-driven HP

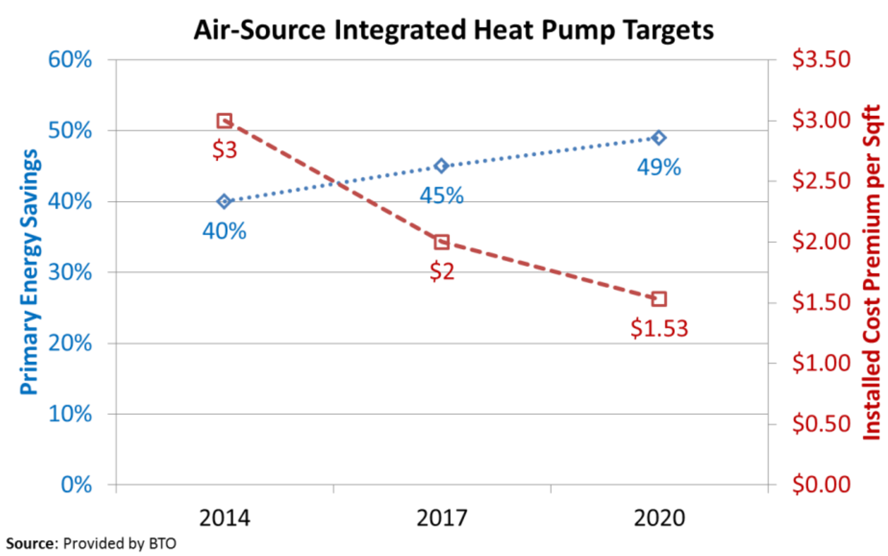
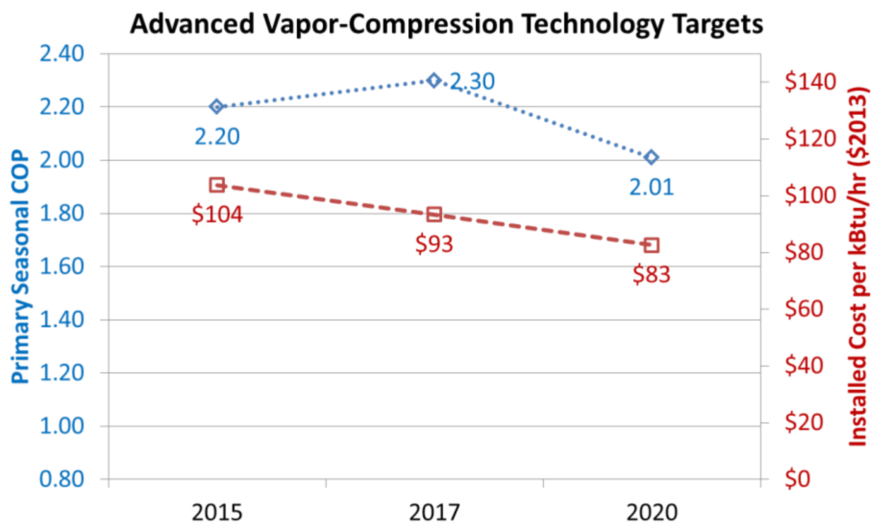
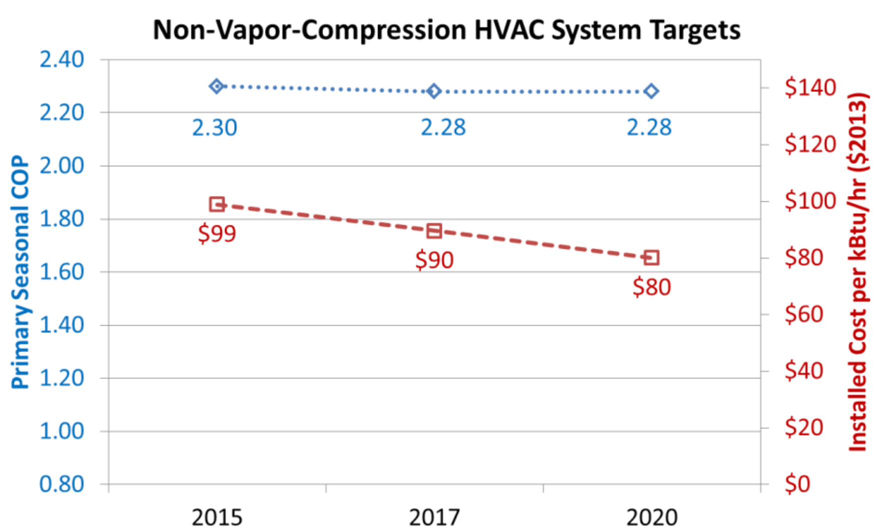


Figure 1-6: Cost and efficiency targets for air-source integrated heat pumps



Source: Provided by BTO

Figure 1-7: Cost and efficiency targets for advanced vapor-compression technologies



Source: Provided by BTO

Figure 1-8: Cost and efficiency targets for non-vapor-compression HVAC systems

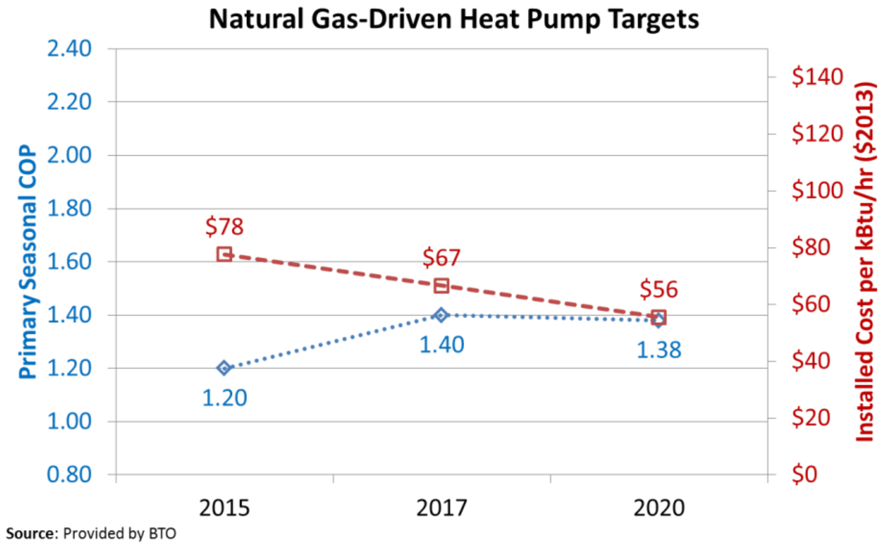


Figure 1-9: Cost and efficiency targets for natural gas -driven heat pumps

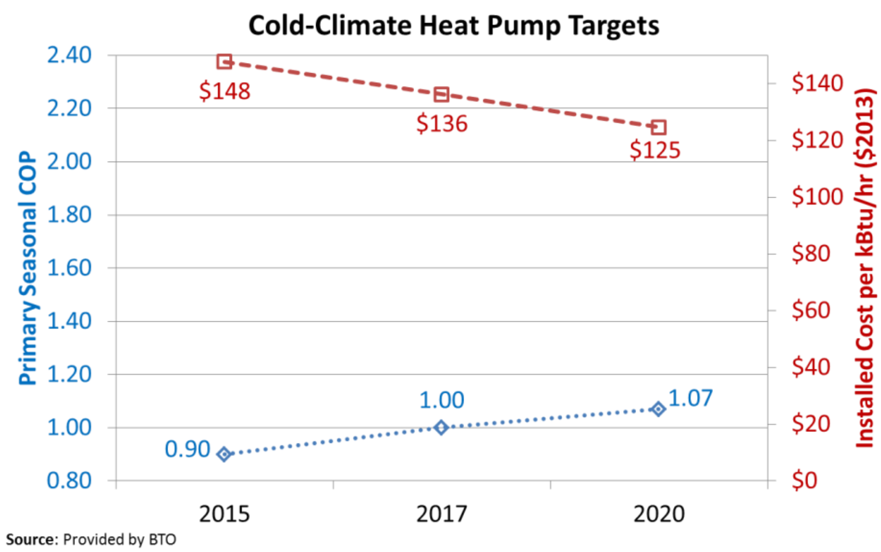


Figure 1-10: Cost and efficiency targets for cold-climate heat pumps

1.2.2 Space Cooling

BTO has focused recent air conditioning (A/C) research on two areas:

- Explore non-vapor-compression technologies
  - Thermoelectric, electrocaloric, magnetocaloric, thermoacoustic, etc.
  - Longer term; represents a potential "step-change" in energy use
  - Eliminates refrigerants.
- Explore separate sensible and latent cooling A/C systems

- Total cooling load is composed of both the sensible load (temperature) and the latent load (humidity)
- 50%–90% savings is possible for technologies optimized for specific climates and applications
- Large portion of the U.S. building stock is located in hot/humid environments.

Table 1-1 outlines some recent activities for space cooling technologies. This work leverages (and benefits from) much of the water heating R&D that BTO conducts. BTO's water heating roadmap covers all water-heating-specific initiatives; an update to the water heating roadmap is currently underway.[6]

Table 1-1: Recent BTO R&D Activities on Space Cooling Technologies

Project	Description / Objective [Project Lead(s)]
(a) Next generation rooftop unit	Develop an initial, high-efficiency rooftop unit (RTU) product intended for introduction into to the U.S. market with an integrated energy efficiency ratio (IEER) of at least 20.0.[7] [ORNL/CRADA-Trane][8]
(b) Efficient window A/C	Develop a high efficiency, 13 EER room air conditioner (RAC).[9] [ORNL]
(c) Rooftop unit w/ integrated active desiccant wheel	Develop a rooftop unit consisting of a cascading vapor-compression and desiccant cooling cycle for enhanced dehumidification [Trane, ORNL, Florida Solar Energy Center]
(d) Low-GWP A/C	Develop a very high performance A/C with low global warming potential refrigerant [United Technologies Research Center and U of Illinois-Urbana Champaign] [10]
(e) Non-vapor-compression cooling	Develop a Non-CFC-based, Critical Flow, Non-Vapor-Compression Cooling Cycle that uses a cycle involving non-equilibrium shocks and cavitation.[11] [PAX Streamline and Kansas State University] [12]
(f) Fan/diffuser w/an evaporative condenser pre-cooler	Improve residential A/C efficiency by 20 – 30% through improvements to condenser technology. The system uses variable frequency drives and rotary compressors to achieve superior efficiency and initial tests show 36–41% efficiency improvement. [13] [Florida Solar Energy Center]

[6] "Research and Development Roadmap for Emerging Water Heating Technologies." prepared by Navigant Consulting, Inc. for BTO. (September 2014.) Accessed September 29, 2014: energy.gov/sites/prod/files/2014/09/f18/WH_Roadmap_Report_Final_2014-09-22.pdf

[7] Information available at: energy.gov/eere/buildings/next-generation-rooftop-unit

[8] Information available at: energy.gov/sites/prod/files/2013/12/f5/emrgtech11_shen_040313.pdf

[9] Information available at: energy.gov/eere/buildings/energy-efficient-window-air-conditioner-ratings-research-project

[10] Information available at: energy.gov/eere/buildings/recovery-act-funded-hvac-projects

[11] Information available at: recovery.gov/arra/Transparency/RecoveryData/pages/RecipientProjectSummary508.aspx?AwardIdSur=130010

[12] Information available at: energy.gov/eere/buildings/recovery-act-funded-hvac-projects

[13] Information available at: energy.gov/eere/buildings/recovery-act-funded-hvac-projects

1.2.3 Space Heating

BTO has focused heavily on advanced heat pump (HP) technologies, especially cold-climate heat pumps (CCHP) and gas-fired HPs. They see these areas as fundamental to future gains in efficiency in space heating. As with A/C, one key area of interest is in non-vapor-compression HP technologies. Table 1-2 provides examples for space heating technologies.

Table 1-2: Recent BTO R&D Activities on Heating Technologies

Project	Description / Objective [Project Lead(s)]
(g) Commercial CCHP	Develop and demonstrate a high-performance commercial CCHP system and will reduce annual electricity use for space heating in cold climates by at least 25%.[14] [United Technologies Research Center]
(h) CCHP	Develop a split system heat pump providing 48,000 Btu/hr. heating capacity with a COP of 4.5 at the 47°F AHRI rating condition, and an efficiency degradation of 50%, and capacity loss of 25% at -13°F ambient conditions.[15] [ORNL and CRADA partner]
(i) Variable speed CCHP	Develop a residential, air-source CCHP that can maintain capacity and efficiency at very low temperatures.[16] The goals are 4.0 COP at 47°F, 3.5 COP at 17°F, and 3.0 COP at -13°F with a payback of <5 years. [Unico]
(j) International HVAC&R R&D collaboration	Provide insight on the latest related HVAC/R technology developments in Europe and the Far East through participation in the International Energy Agency (IEA) Heat Pump Programme (HPP) and also through the International Institute of Refrigeration (IIR). [ORNL]
(k) Natural refrigerant high efficiency commercial HP	Develop a regenerative air source HP for commercial applications that uses air (R729) as the working fluid, thereby eliminating all HFC refrigerants. The HP will have a 20-ton capacityand a 240 kBtu/hr heating capacitywith a payback of four years.[17] [S-RAM Dynamics with: ORNL, ReGen, Purdue]
(l) Low-cost gas heat pump for building space heating	Develop a low-cost, gas-fired absorption air-source HP (80 kBtu/hr.) for high efficiency space heating to reduce heating costs by 30-45% compared to conventional gas furnace/boiler technologies. The HP reaches a coefficient of performance of 1.4 at 47°F and 1.2 at -13°F using a simple, single-effect ammonia-water absorption cycle. [18] [Stone Mountain Technologies, Inc.]
(m) Natural refrigerant high-efficiency HVAC	Design, develop and demonstrate a natural refrigerants based very high efficiency residential A/C system that provides a 30% reduction in annual energy consumption.[19] [United Technologies Corporation]

[14] Information available at: www.eere.energy.gov/pdfs/building_envelope_hvac_foa_selection_projects_list.pdf
[15] Information available at: energy.gov/eere/buildings/cold-climate-heat-pump-research-project
[16] Information available at: www.eere.energy.gov/pdfs/building_envelope_hvac_foa_selection_projects_list.pdf
[17] Information available at: energy.gov/eere/buildings/downloads/natural-refrigerant-high-performance-heat-pump-commercial-applications
[18] Information available at: www.eere.energy.gov/pdfs/building_envelope_hvac_foa_selection_projects_list.pdf and energy.gov/eere/buildings/recovery-act-funded-hvac-projects
[19] Information available at: energy.gov/eere/buildings/recovery-act-funded-hvac-projects

Project	Description / Objective [Project Lead(s)]
(n) High performance CCHP	Develop, test, and evaluate HPs (40–60 kBtu/hr.) that utilize: (1) Both flooded compression with regeneration, and cooled compression with economizing; (2) Low-cost flow control devices to evenly distribute two-phase refrigerant in the evaporator; 3) Cycle optimization to integrate both technologies above.[20] [Purdue, Emerson Climate Technologies]
(o) Supercharger for CCHP	The project aims to develop the essential elements of a "HP furnace," which will allow efficient operation in the coldest U.S. climates with zero backup heat. The technology will add a second compressor that operates automatically on cold days to boost refrigerant pressure and temperature.[21] [Mechanical Solutions, Inc.]
(p) High performance CCHP	Develop, test, and evaluate a high performance and cost-effective vapor-compression heat pump for use in cold-climate regions. It is anticipated that these system improvements can be implemented with modest consumer price premiums since they are primarily built on already commercialized, mature technologies.[22] [Purdue]

1.2.4 Integrated Water Heating and Space Conditioning Systems

BTO has also focused extensively on integrated HVAC equipment that serves multiple loads, including space cooling/heating and water heating. The integrated heat pumps (IHP) that BTO has supported include air-source (AS-IHP), ground-source (GS-IHP), and fuel-fired IHP systems. The concept is to merge several end-use together into a new solution that benefits from energy cascading where the waste (or residual) heat from one process provides the energy input for another. For example waste heat from A/C can be used to heat water. Table 1-3 summarizes select recent BTO R&D activities for IHP systems.

Table 1-3: Recent BTO R&D Activities on Integrated Technologies

Project	Description / Objective [Project Lead(s)]
(q) Develop standard method of test for IHP	Develop an ASHRAE standard for a method of test for IHPs; develop an AHRI rating standard for IHPs.[23] [ORNL]

[20] Information available at: recovery.gov/arra/Transparency/RecoveryData/pages/RecipientProjectSummary508.aspx?AwardIdSur=105093 and energy.gov/eere/buildings/recovery-act-funded-hvac-projects
[21] Information available at: energy.gov/sites/prod/files/2013/12/f5/emrgtech15_walter_040313.pdf and energy.gov/eere/buildings/recovery-act-funded-hvac-projects
[22] Information available at: recovery.gov/arra/Transparency/RecoveryData/pages/RecipientProjectSummary508.aspx?AwardIdSur=105093 and energy.gov/eere/buildings/recovery-act-funded-hvac-projects
[23] Information available at: energy.gov/eere/buildings/downloads/standard-method-test-integrated-heat-pumps

Project	Description / Objective [Project Lead(s)]
(r) Two stage AS-IHP	This IHP provides heating, ventilation, and A/C and water heating to residences at 40–45% energy savings vs. conventional minimum efficiency equipment by utilizing a two-stage vapor-compression system.[24] [ORNL]
(s) Variable speed AS-IHP	Develop a variable speed AS-IHP that closely matches part-load needs and improves efficiency.[25] The technology will provide 45% to 55% energy savings vs. minimum efficiency equipment. [ORNL/CRADA- Nordyne]
(t) Variable speed ground source-IHP (GS-IHP)	Develop a ground-source integrated heat pump that provides 55% to 65% energy savings vs. minimum efficiency equipment suite. The technology serves 100% of the home's heating, cooling, and water heating needs and is about 30% more efficient than other available ground-source heat pumps (GHP).[26] [ORNL]
(u) AS-IHP and GS-IHP field tests	Produce quality field data on the GS-IHP and AS-IHP products for manufacturers to use in refining system design. ORNL is testing these systems at four unoccupied test houses at the ZEBRAlliance test site.[27] [ORNL]
(v) Advanced GHP technology for very-low-energy buildings	Accelerate GHP deployment by developing and identifying new technologies that reduce cost and/or improve performance. The focus area is smart controls for hot water that optimizes the tank's temperature schedule based on usage patterns for 10% savings. [ORNL – U.S. China Clean Energy Research Center, CERC]
(w) Multi-function fuel-fired HP	Develop a gas-fired IHP with four ton capacity to serve heating, cooling, and water heating with a goal for cooling COPs of 1.3 and a heating COPs of 1.5. The unit aims to achieve an 80% reduction in water heating energy consumption with a 1 to 2 kilowatt electricity generation capability for ancillary loads, and a 5 year payback.[28] [29] [ORNL/CRADA]
(x) Natural gas heat pump and air conditioner	Commercialize a Vuilleumier-based natural gas heat pump to provide heating, cooling and hot water for homes and commercial buildings without the use of harmful refrigerants and targets up to 200% efficiency improvements for space heating, and 150% efficiency improvements for water heating and space cooling.[30] [31] [ThermoLift and partners]

[24] Information available at: energy.gov/sites/prod/files/2014/05/f15/HVAC_Overview_Bouza_042314_and_042414.pdf
[25] Information available at: energy.gov/eere/buildings/advanced-variable-speed-air-source-integrated-heat-pumps-research-project
[26] Information available at: energy.gov/articles/technology-breakthrough-geothermal
[27] Information available at: energy.gov/eere/buildings/hvac-water-heater-field-tests-research-project
[28] Information available at: energy.gov/sites/prod/files/2013/12/f5/et_overview_phelan_040213.pdf
[29] Information available at: energy.gov/eere/buildings/multi-function-fuel-fired-heat-pump-research-project
[30] Information available at: energy.gov/articles/energy-department-invests-save-heating-cooling-and-lighting
[31] Information available at: www.eere.energy.gov/pdfs/et_selections_0823.pdf

1.2.5 Cross Cutting

BTO also conducts R&D on many other related and cross-cutting technologies, much of which can be leveraged to further HVAC BTO R&D objectives. These topics include:

- Covered in this roadmap
  - Controls
  - Heat exchangers
  - Ventilation
  - Compressors.
- Covered in other BTO R&D roadmaps
  - Refrigerants – See BTO refrigerants roadmap, last published July 2011, with an update currently underway[32]
  - Water heating – See BTO water heating roadmap, published September 2014.[33]

Water heating in particular is an area with significant overlap with HVAC R&D given the focus on electric and gas-fired HP technologies. Much of what is covered in the water heating roadmap on HP technologies is valuable to advancing HVAC technologies. Table 1-4 summarizes select BTO cross-cutting activities.

Table 1-4: Recent BTO R&D Cross-Cutting and Related Activities

Project	Description/Objective [Project Lead(s)]
(y) Rotating heat exchanger for residential HVAC	This project will demonstrate a rotating heat exchanger technology in residential HVAC that could improve cycle efficiency and enable increased use of HPs in cold climates.[34] [Sandia National Laboratory(SNL)/ORNL]
(z) Miniaturized air-to-refrigerant heat exchangers	This project will design and build prototypes of miniaturized air-to-refrigerant heat exchangers with10kW capacity with at least 20 percent less volume and 20 percent less material compared to traditional designs.[35] [University of Maryland]
(aa) Building integrated heat and moisture exchange	Achieve lower energy use at better cost and at increasing scale through advanced energy recovery ventilation (ERV) that is incorporated into the walls of a building via panels (AirflowTM panels). The project team is conducting pilot installations and validated testing at various scales.[36] [Architectural Applications, Inc.]

[32] "Research and Development Roadmap for Next-Generation Low-Global Warming Potential Refrigerants." Report by Navigant Consulting, Inc. for BTO. (July 2011) Accessed September 2, 2014: energy.gov/sites/prod/files/2014/07/f17/next_generation_refrigerants_roadmap.pdf

[33] "Research and Development Roadmap for Emerging Water Heating Technologies," prepared by Navigant Consulting, Inc., for BTO. (September 2014) Accessed September 29, 2014: energy.gov/sites/prod/files/2014/09/f18/WH_Roadmap_Report_Final_2014-09-22.pdf

[34] Information available at: www.eere.energy.gov/pdfs/et_selections_0823.pdf

[35] Information available at: www.eere.energy.gov/pdfs/building_envelope_hvac_foa_selection_projects_list.pdf

[36] Information available at: energy.gov/eere/buildings/downloads/building-integrated-heat-and-moisture-exchange

Project	Description/Objective [Project Lead(s)]
(bb) Hybrid ventilation optimization and control R&D	Develop quick, easy-to-use tools that optimize ventilation control strategies in commercial buildings with a focus on maximizing use of natural ventilation. The project is being conducted by the U.S.-China Clean Energy Research Center (CERC), an R&D consortium bringing together key stakeholders to develop a long-term platform for U.S.-China joint R&D.
(cc) Radial flow bearing heat exchanger	Demonstrate a radial flow cooler in HVAC&R systems for savings of 15%–20%. In addition, the project is building and testing an axial flow heat pump based on the advances in the radial flow cooler that is scalable to building HVAC&R applications. The axial cooler eliminates any requirement for heat transfer across a fluid bearing and creates a new de facto standard for cost-competitive, high-efficiency HVAC&R technology.[37] [SNL]
(dd) Advanced HVAC	Optimize the operation of existing cooling and dehumidification systems, and develop improved HVAC systems through the U.S.-India Joint Center for Building Energy Research and Development (CBERD). The long-term goal is to integrate an energy-efficient non-compressor dedicated outdoor air system (DOAS), which could improve performance by up to 30%.[38] [ORNL]
(ee) Advanced compressor designs	Develop a variable-capacity refrigerator using a linear compressor and other novel features, that offers the potential to reduce energy use by up to 40% compared with current refrigerators. This proposal focuses on modeling, developing conceptual system design and the architecture, and preliminary testing of components, such as calorimeter testing of the linear compressor, leading to developing a revolutionary refrigerator concept.[39] [ORNL]
(ff) Thermodynamic evaluation of low-global-warming-potential refrigerants	Evaluate alternative refrigerants with low GWP to identify the best candidate fluids and the trade-offs among them. In this context, "best" is determined primarily by a fluid's performance in the vapor-compression cycle. The final goal is to evaluate, identify, and publish a list of low-GWP working fluids along with thermophysical properties that yield high energy efficiency. NIST will lay out the tradeoffs for consideration by the refrigeration industry. [40] [NIST]
(gg) RTU smart monitoring and diagnostics system (SMDS)	A low-cost smart remote condition monitoring and diagnostic system allows new and existing packaged units to easily incorporate continuous monitoring and fault detection. The system provides building owners and operators with a simple way to identify performance degradation, quantify operating costs, and enables smarter maintenance decisions.[41] [ORNL]
(hh) RTU controls	Develop advanced RTU controllers to incorporate several energy-saving features onto existing equipment (e.g., integrated economizers, variable capacity control, demand-controlled ventilation). These capabilities improve part-load efficiency and also allow remote monitoring/diagnostics.[42] [PNNL]

[37] Information available at: energy.gov/eere/buildings/downloads/radial-flow-bearing-heat-exchanger
[38] Information available at: energy.gov/eere/buildings/downloads/advanced-hvac-systems
[39] Information available at: energy.gov/eere/buildings/downloads/advanced-compressor-technologies
[40] Information available at: energy.gov/eere/buildings/downloads/thermodynamic-evaluation-low-global-warming-potential-refrigerants-0
[41] Information available at: energy.gov/sites/prod/files/2013/12/f5/commlbldgs16_brambley_040413.pdf
[42] Information available at: energy.gov/sites/prod/files/2013/12/f5/commlbldgs16_brambley_040413.pdf

Project	Description/Objective [Project Lead(s)]
(ii) VOLTTRON Lite	Develop, demonstrate, and propagate an open-source, open-architecture platform to enable advanced communication and control capabilities for major building systems, including HVAC. VOLTRON Lite represents a common integrating platform that coordinates the transactions with different systems, data historians, grid signals, and other network agents.[43] [PNNL]
(jj) Magnetic refrigerant materials	Develop high-performance magnetic refrigerant materials that will significantly enhance the efficiency and commercialization potential of magnetic refrigeration systems (a non-vapor cycle). The new materials should require a weaker magnetic field to operate and contain less expensive raw materials. The proposed work will enable a 30% increase in efficiency of refrigeration and cooling technology, and will eliminate harmful refrigerants.[44] [GE]
(kk) Non-CFC, non-vapor-compression	Develop a novel refrigeration system that uses a cycle involving non-equilibrium shocks and cavitation. This novel refrigeration cycle allows for a substantial improvement in the COP and the use of a wide range of environmentally benign and low-cost refrigerants.[45] [PAX]

1.3 Technology and Market Scope

This roadmap has a broad scope, encompassing space cooling, heating and ventilation technologies, thermal distribution equipment, controls, and more. Figure 1-11 shows a high level summary (not exhaustive) of the technologies covered in this roadmap.

[43] Information available at: www.pnl.gov/main/publications/external/technical_reports/PNNL-22935.pdf
[44] Information available at: energy.gov/eere/buildings/recovery-act-funded-hvac-projects
[45] Information available at: energy.gov/eere/buildings/recovery-act-funded-hvac-projects

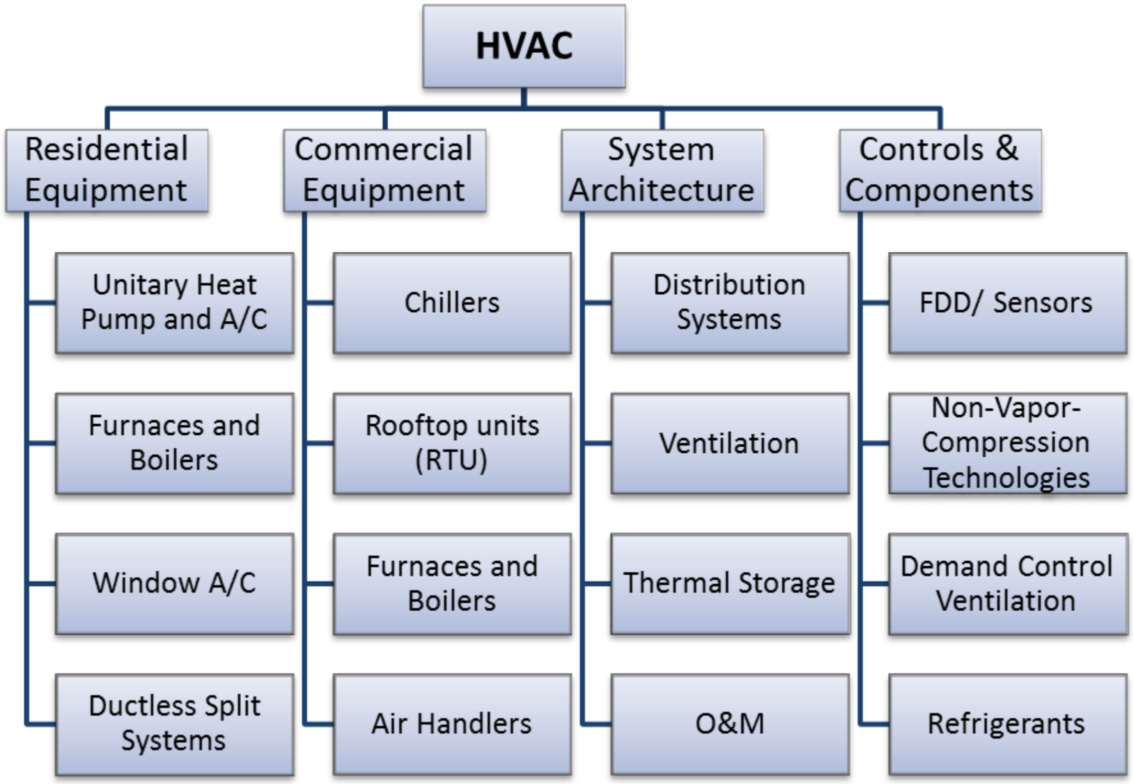


Figure 1-11: HVAC roadmap technology scope (not exhaustive)

Not all technologies are emphasized equally or even included in the articulated initiatives in Section 4. Inclusion in the initiatives requires that the technology, among other things, has promising opportunity to help meet BTO goals and fits with BTO mission and capabilities. For example, while the roadmap covers gas-fired furnaces, we identified no associated priority initiatives in the course of the development process (see Section 2 for additional detail on the process).

In supporting development and commercialization of these technologies, BTO focuses their efforts on innovative initiatives that accelerate development of technologies. However, in select cases, BTO also supports initiatives that can drive innovation broadly throughout the industry and enable future breakthroughs. These two types of initiatives are:

- **Direct-impact initiatives** – R&D that targets technical innovations in a specific component, system, or type of technology that will directly provide energy savings, e.g., development of improved heat exchangers for vapor-compression systems. See Section 4.2 for direct-impact technology initiatives.
- **Enabling initiatives** – R&D that indirectly aids improvements in energy efficiency through development of supplementary technologies (e.g., sensors) or through advances in processes (e.g., manufacturing) or knowledge (e.g., data collection) that benefits many types of technologies, e.g., development of modeling software. See Section 4.3 for enabling technology initiatives.

This roadmap does not address early stage science research that is more suitable for the Office of Science, or late-stage market development activities that may be more suitable for industry or for the commercial or residential buildings groups (separate from the Emerging Technologies group) within BTO.

1.4 Objective of This Roadmap

The objective of this roadmap is to provide a pathway to achieving BTO's goal of reducing HVAC-related building energy consumption. In this roadmap, we aim to identify and prioritize research and development (R&D) initiatives that provide the best opportunities for accelerating development and commercialization of emerging energy-efficient HVAC technologies.

This roadmap characterizes the current state of the market and of emerging HVAC technology research. BTO's efficiency and cost targets for emerging technologies, as discussed in Section 1.1, above, define the end state for HVAC technology achievements by 2030. This roadmap aims to provide the pathway that connects the current state of HVAC technologies with the 2030 target state.

2 Roadmap Approach

Figure 2-1 outlines the four stages for developing this roadmap.

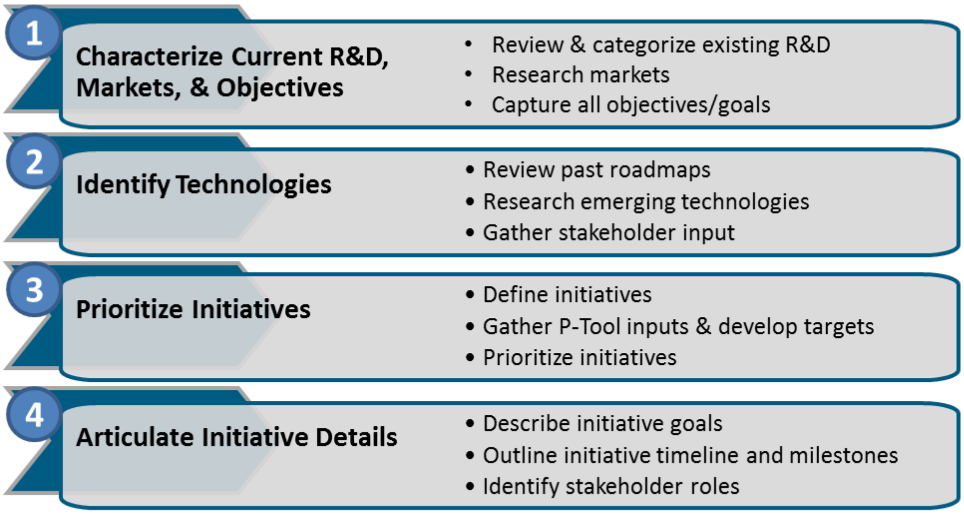


Figure 2-1: Roadmap development stages

2.1 Stage 1: Characterize Current R&D, Markets, and Objectives

Key to the success of this roadmap is the clear characterization and understanding of current markets and R&D activities, as well as the desired future state of HVAC technologies and overarching goals of the organization. In Stage 1 we researched and analyzed these topics, resulting in the overviews provided in Sections 1and 3. Examples of reviewed resources include (but are not limited to):

- Past HVAC R&D roadmaps (e.g., HVAC, GHP, water heating)
- BTO technical and market reports on HVAC technologies
- BTO program peer review presentations
- EIA installed base data
- Equipment shipment data.

These background data lay the foundation for the roadmap and define the current state of HVAC equipment and markets. Further, it puts greater context around the level of effort required to reach BTO's future goals.

2.2 Stage 2: Identify Technologies

To identify R&D initiatives, Navigant aggregated inputs from three different sources:

1. **Literature review** – research and analysis of academic papers, industry reports, national laboratory activities, and patent fillings regarding emerging opportunities for HVAC research.
2. **Stakeholder forum** – stakeholder input from the June 2014 HVAC stakeholder forum at the ASHRAE headquarters in Atlanta, GA.
3. **One-on-one interviews** – detailed input from individual industry experts on emerging HVAC technologies; included both forum attendees and non-attendees.

The forum, held on June 17, 2014, brought together stakeholders and industry experts to discuss barriers, new ideas and technologies, and strategic pathways to help achieve BTO's energy savings goals. The group consisted of 51 individuals representing manufacturers, academic researchers, national laboratories, gas and electric utilities, energy-efficiency organizations, and trade organizations. The six-hour forum included a variety of opportunities to gather feedback and foster discussion around key challenges in accelerating development and adoption of high-efficiency HVAC technologies. In addition to group dialogue and brainstorming, the forum also utilized small break-out group discussions to generate intimate discussions in more specific topics areas, including:

- **Session 1 & 2** (repeated topics – attendees participated in two different sessions):
  - Residential and small commercial heating/cooling
  - Large commercial heating/cooling
  - Controls, software, interfaces, usability, and data.
- **Session 3:**
  - Distribution and ventilation
  - System architecture (e.g., combination space and water heating systems, central vs. distributed, storage, etc.)
  - Outside the box (e.g., renewable integration, non-vapor-compression, etc.).

Participants voted on the initiatives generated during the forum based on their perceived impact and importance to the industry; these votes became inputs to the prioritization process (see Section 2.3). After the forum, Navigant reviewed the list of initiatives and selectively conducted one-on-one interviews with stakeholders (both forum participants and non-participants) on topic areas that required additional clarification. For additional information on the forum, see Appendix A – HVAC Forum Summary Report.

2.3 Stage 3: Prioritize Initiatives

To prioritize the initiatives and identify the best opportunities for BTO to pursue, we followed a three-step process:

1. **Preliminary ranking** (high, medium, low priority) – low priority were removed from further prioritization steps

2. **Qualitative scoring** – a multivariate, matrix-based scoring for all high and medium priority initiatives
3. **Quantitative scoring** – rescoring of top high priority direct-impact initiatives using BTO's Prioritization Tool (P-Tool) – results were used to rescore these initiatives and re-rank them among all high and medium priority initiatives.

The final output was a prioritized list of initiatives in three different priority tiers. Figure 2-2 summarizes the prioritization process. The following subsections describe each step.

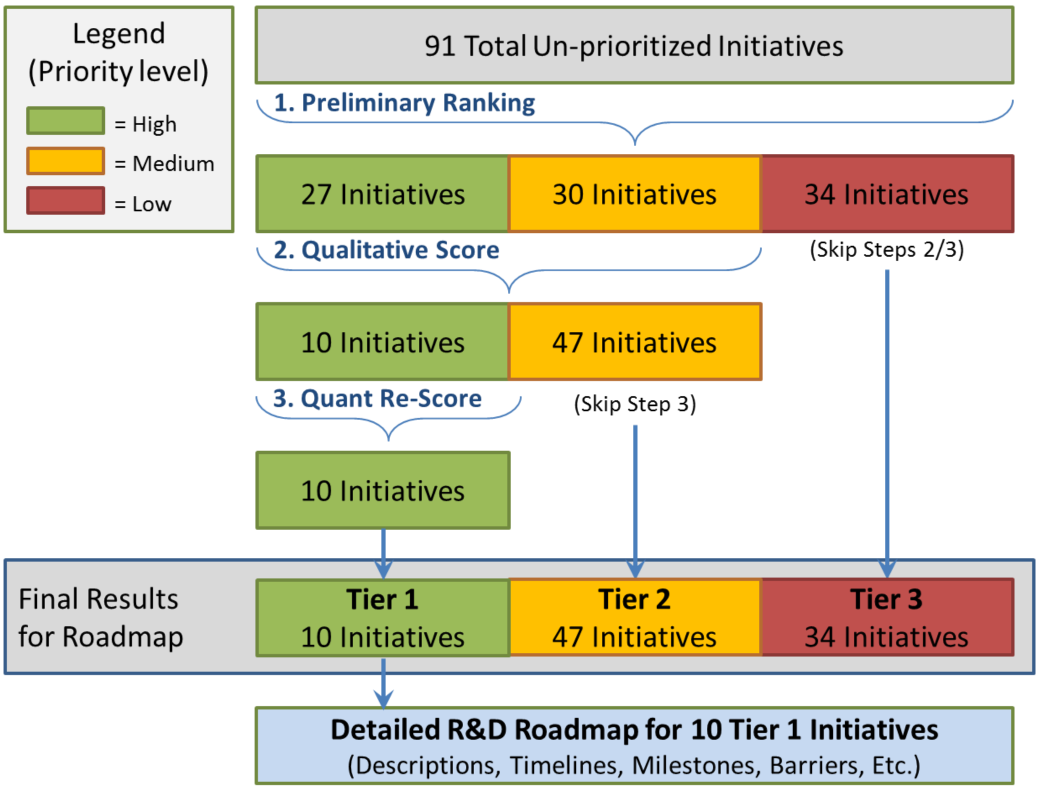


Figure 2-2: Prioritization process steps

The Tier 1 initiatives are those which this roadmap articulates in the greatest detail in Section 4, including timelines, milestones, barriers, and role and responsibilities.

2.3.1 Preliminary Ranking

We developed preliminary rankings of all 91 unique initiatives from our outreach and research activities based on the following sources:

- Forum participant votes
- General feedback via follow-up interviews
- Internal research and expertise.

Each priority level contained approximately 1/3 of the total number of initiatives. In the interest of time, this preliminary ranking provided general guidance on the approximate level of time and effort to be spent on refining the qualitative and quantitative scoring in the following steps.

2.3.2 Qualitative Prioritization

We labeled each initiative as either: "enabling" or "direct-impact" (see discussion in Section 1.3, above). Two different individuals independently scored each of the medium and high priority initiatives (based on preliminary rankings) on five different metrics. Table 2-1 defines each metric and Table 2-2 shows the scoring legend on a scale of 1 to 5. A higher score in each metric is better. Both the metrics and weights were developed in close coordination with BTO to ensure that the prioritization approach accurately reflects their objectives.

Table 2-1: Initiative Scoring Metrics - Definitions

Metric	Definition
Impact (Direct-impact initiatives)	**Impact on Energy Savings Potential** – Estimated technical savings potential (assuming 100% adoption) of target markets relative to other initiatives
Impact (Enabling initiatives)	**Impact on Knowledge Gap or Adoption Barrier** – Expected impact on addressing a critical knowledge gap or overcoming a barrier to adoption of high-efficiency HVAC technologies
Fit with BTO Mission	Suitability of initiative (e.g., research stage and needs) to BTO's mission, goals, and capabilities (including the initiative's expected time to market)
Criticality of BTO Involvement	Criticality of BTO participation to the success of the initiative
Level of Risk	Funding level that may be expected for the initiative to be successful
Level of Required Investment	Expected investment risk based on the likelihood of the initiative achieving impact

Table 2-2: Initiative Scoring Metrics – Scoring Legend

Metric	5	4	3	2	1	Wgt:
Impact	Significant	Semi-Significant	Moderate	Modest	Minimal	**30%**
Fit with BTO Mission	Core to mission	Semi-core to mission	Relevant to mission	Semi-relevant to mission	Outside scope / mission	**20%**
Criticality of BTO Involvement	Critical to success	Semi-critical to success	Beneficial to success	Semi-beneficial to success	Unnecessary for success	**20%**
Level of Risk*	Low	Low-Moderate	Moderate	High-Moderate	High	**10%**
Level of Required Investment	< $1M	$1M – $3M	$3M – $5M	$5M – $10M	> $10M	**20%**

*We score Level of Risk relative to BTO mission and goals. Accordingly, low risk for these initiatives may still be considered high risk to a manufacturer or other industry stakeholder.

The output scores for each metric consisted of an average from each scorer, which we then averaged together using the weightings in Table 2-2. In order to incorporate voting from the stakeholder forum (see Section 2.2, above), we assigned an industry-input score (0-5) to each initiative, depending on the relative number of votes. Each point on the industry-input score corresponded to a boost in final score of 0.05 (applied after scoring of prioritization metrics from above). For example, an initiative with a prioritization score of 3 and an industry-input score of 4 would receive a final score of 3.20 (i.e., $3 + (0.05)4 = 3.20$).

2.3.3 Quantitative Prioritization – BTO P-Tool – Direct-Impact Initiatives Only

The 10 direct-impact initiatives scored as high priority in the qualitative analysis underwent a quantitative scoring process for overall initiative impact using BTO's P-Tool. The P-Tool compares investment opportunities across all of BTO to help inform decision making and goal/target development. The National Renewable Energy Laboratory (NREL) originally developed the tool and described it in more detail in their project report.[46] In brief, the tool uses inputs for energy measure performance, cost, market, and lifetime to analyze each measure both individually and as part of a full portfolio of measures. No fuel switching options are included in the analysis where installation of the new technology requires changing from one fuel to another. The tool produces three key outputs:

- **Technical Potential (TBtu):** The annual energy savings achieved if the new measure replaces all existing stock in the U.S., i.e., 100% adoption. This represents the theoretical maximum energy savings and does not account for penetration-limiting factors.
- **Un-staged Maximum Adoption Potential (TBtu):** The portion of the technical potential achieved through deployment of the technology for all end-of-life replacements and new purchases by accounting for sales, disposals, and building stock growth.

[46] Philip Farese, et. al., "A Tool to Prioritize Energy Efficiency Investments." NREL Technical Report. (August 2012) Accessed September 2, 2014: www.nrel.gov/docs/fy12osti/54799.pdf.

- **Staged Maximum Adoption Potential (TBtu):** The portion of the un-staged maximum adoption potential achieved when accounting for competition among technologies, thereby avoiding double counting savings for measures with overlapping markets. The P-Tool attributes savings potential to competing technologies based on the cost of conserved energy (CCE), i.e., the technology with the lowest CCE is the first to capture its share of a given market. The P-Tool then attributes incremental savings potential to the technology with the next higher CCE and higher energy savings potential. The P-Tool determines staged maximum adoption potential on an individual market by market basis.

Section 4.2 provides detailed P-Tool outputs for each direct-impact initiative and provides detailed discussion of Tier 1 initiatives. These data enable BTO to further discern which HVAC initiatives provide the greatest benefit relative to other investments across any end-use and help determine appropriate initiative performance and cost targets.

We rescored each high priority direct-impact initiative's Impact score based on the P-Tool's staged maximum adoption potential value using the legend in Table 2-3.

Table 2-3: Direct-Impact Quantitative Scoring Metrics – Scoring Legend

Metric	5	4	3	2	1	Wgt:
Impact (TBtu/yr.) (Direct-impact)	> 750	750 – 500	500 – 250	250 – 10	< 10	**30%**
Basis:	P-Tool results for Staged Maximum Adoption Potential					

2.4 Stage 4: Develop R&D Roadmap

As the final step in the roadmap development process, we developed detailed descriptions of all 10 Tier 1 initiatives from the prioritization process. Each initiative description includes:

- *Description* – General discussion of the technology/topic and the markets, applications, etc. where it applies
- *Purpose/objective* – Intended emphasis of R&D activities, including specific expected improvements that researchers should aim to achieve
- *Key technical challenges*– Initiative-specific technical challenges that researchers will have to address to achieve targets
- *Timeline with key milestones* – Pathway to achieving intended outcomes for the initiative, including short, medium, and long term steps and milestones as applicable
- *Potential impact on existing market barriers* – specific impacts achievable via the initiative to address challenges in the market
- *Recognize key stakeholder roles and responsibilities* – Clear articulation of actions that should be undertaken by various industry players in order to be successful.

Section 4 of this report contains all the roadmap details for the initiatives.

3 Market Overview

3.1 Residential Equipment Landscape

In their 2009 residential energy consumption survey (RECS), EIA documented nearly 115 million homes in the U.S. For more than 55 million of those homes, natural gas was the predominant fuel.[47] Nearly 45 million of these homes heated with warm-air furnaces. Figure 3-1 summarizes residential heating equipment installed base by fuel and by equipment type. Appendix A contains additional information on space heating fuels.

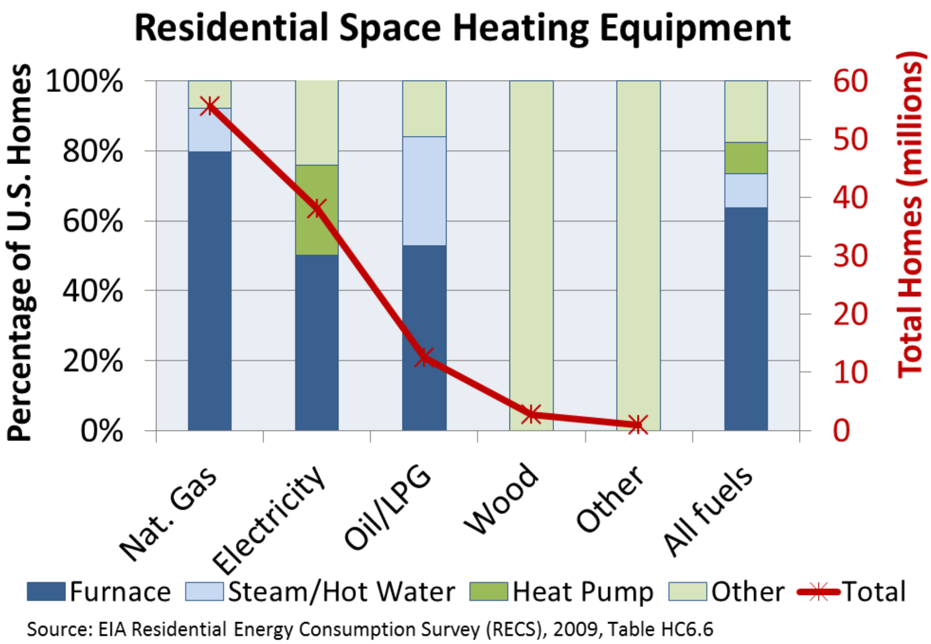


Figure 3-1: Residential space heating equipment by fuel type

Residential space cooling operates nearly 100% on electricity, running ducted central A/C systems, ducted central HPs, or window/wall A/Cs. Fossil fuel-based space cooling systems are under development but are not currently available to the typical customer. The percentage of homes using various types of equipment varies by region. For example, homes in cold or mixed-humid climates have much greater percentages of window A/Cs than other climates. Figure 3-2 summarizes residential space cooling equipment by climate and equipment type.

[47] EIA. 2009. "Residential Energy Consumption Survey." U.S. Energy Information Agency. Accessed September 2, 2014: www.eia.gov/consumption/residential/data/2009/

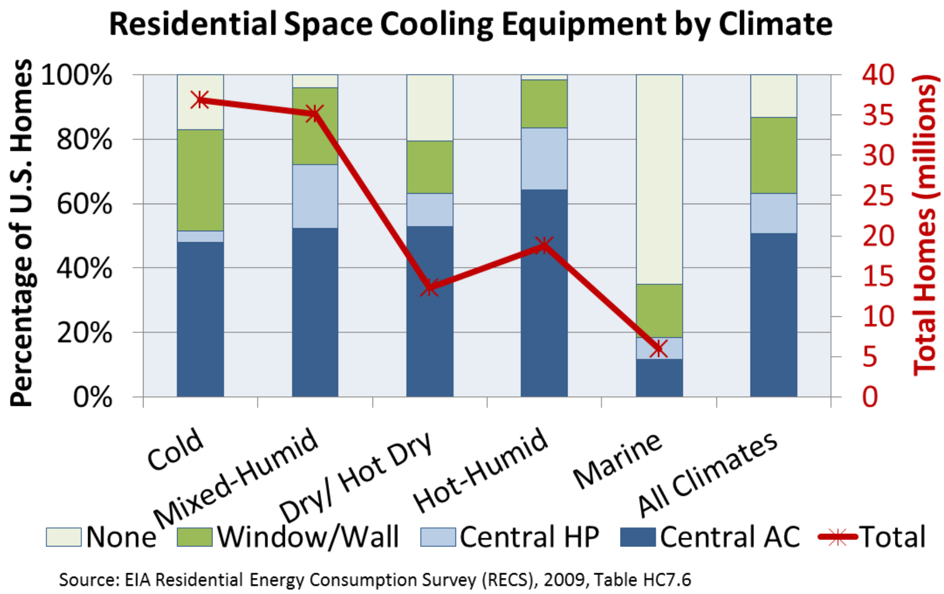


Figure 3-2: Residential space cooling equipment by climate

3.2 Commercial Equipment Landscape

EIA last completed their Commercial Building Energy Consumption Survey (CBECS) in 2003, and found more than 4.8 million commercial buildings in the U.S., constituting more than 71 billion square feet of floor space. Since the publication of those survey data, EIA has published preliminary summary results showing that as of 2012, the building stock had grown to more than 5,500,000 commercial buildings, constituting more than 87 billion square feet of floor space.[48]

Commercial buildings use a more even split of equipment types (even across various regions of the country) than residential buildings. HPs are most common in the south, furnaces in the Midwest, boilers in the northeast, and packaged heaters in the west; Figure 3-3 summarizes the space heating equipment in these buildings; overall, no single equipment type serves more than 23% (for boilers) of commercial floor space. Appendix A contains additional information on commercial space heating fuels.

[48] EIA. 2012. "Commercial Building Energy Consumption Survey." U.S. Energy Information Agency. Preliminary results available at: www.eia.gov/consumption/commercial/; complete results from the last survey in 2003 available at: www.eia.gov/consumption/commercial/data/2003/.

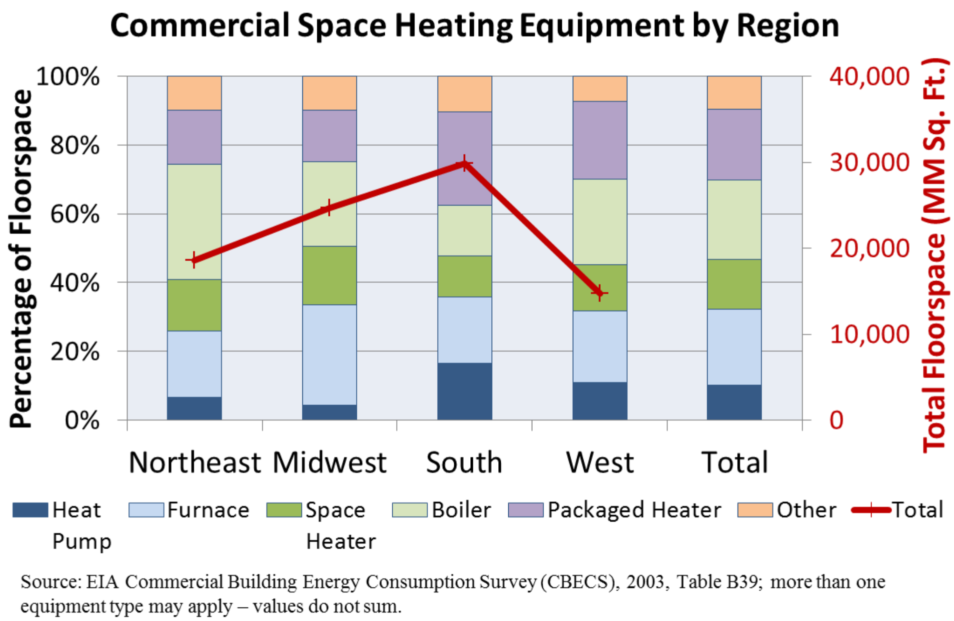


Figure 3-3: Commercial space heating equipment by region

For commercial space cooling, packaged equipment (e.g., rooftop units, RTUs) is the most common, serving 38% of the floor space overall, with very similar percentages in each individual region. The west, with 13% of the floor space served by "other" equipment includes the greatest number of swamp coolers – serving 1,300 million square feet. "A/C Units", including packaged terminal air conditioners (PTAC) and through the wall A/Cs, are most common in the Northeast, where 23% of floor space is cooled with this equipment. "Central A/C" in this survey refers to residential split-system central A/C – most common in the commercial sector in small buildings. Figure 3-4 provides detail on commercial space cooling equipment in the country.

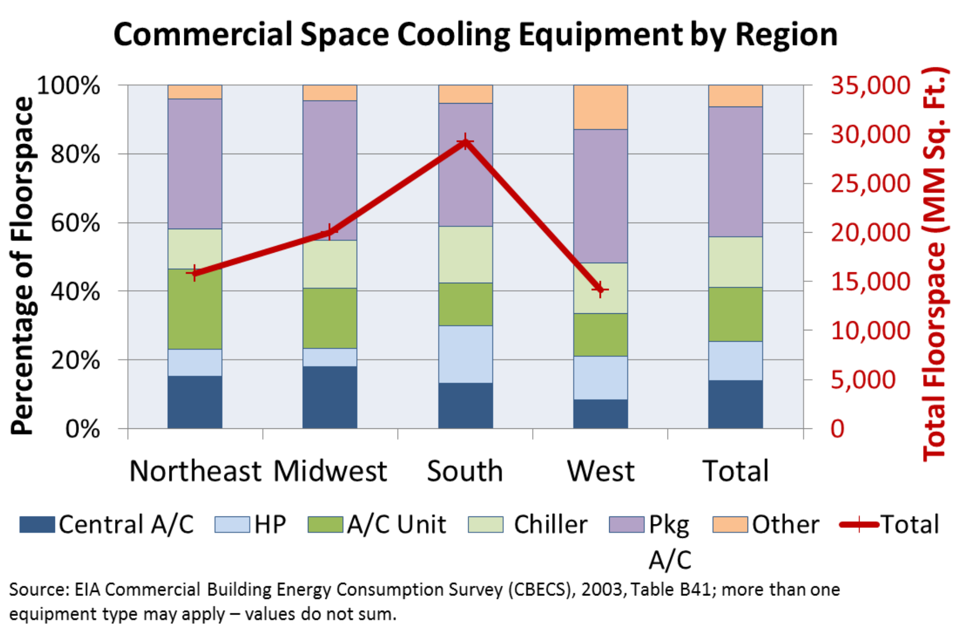


Figure 3-4: Commercial space heating equipment by region

3.3 State of the HVAC Market – Equipment Trends

Much of the HVAC equipment market consists of low or minimum efficiency equipment. Of the residential central A/C products sold by ENERGY STAR partner manufacturers, 32% and 20% of sales of residential central A/Cs and air-source HPs, respectively, were for ENERGY STAR qualified products. Similarly, 22% of sales of light commercial HVAC equipment were for ENERGY STAR qualified products. These percentages drop when looking at the entire market (i.e., including manufacturers that do not sell ENERGY STAR qualified products).[49]

However, some emerging technologies are changing the equipment landscape and making inroads in support of DOE's energy savings targets. Four areas worthy of closer inspection include:

- **Renewable thermal-integrated systems** – Renewable thermal systems have been in existence for many decades in some cases. Solar thermal and biomass heating systems were pioneered on a commercial scale during the 1970s. Recent policy initiatives (mostly on a state by state basis) have helped to start building the renewable thermal industry. Depending on the state, renewable thermal HVAC systems may include solar thermal space heating (and cooling), biomass heating, ultra-high-efficiency GHPs, and ultra-high efficiency air-source HPs (e.g. Variable speed mini-split ductless). For example, in 2012 New Hampshire added renewable thermal energy to the state's Renewable Portfolio Standard, making geothermal, biomass, and solar thermal eligible for renewable energy credits (effective June 2014).[50] In nearby Massachusetts in July 2014, the state legislature passed legislation that enables renewable thermal technologies to qualify for Alternative Energy Credits under the state's Alternative Energy Portfolio Standard.[51] While market share of these technologies is still very small, such support may help drive growth in the coming years.
- **Mini-split (and multi-split) HPs** – Mitsubishi and Daikin, among others, have popularized ductless HPs and A/Cs in Asia and Europe. Also known as mini-split or multi-split systems, they are among the most efficient available, but until recently, have not gained much traction in the U.S. Some systems can achieve 23 SEER, nearly 60% higher than the ENERGY STAR minimum specification (14.5 SEER for split systems).[52]
- **Ultra-High Efficiency RTUs** – BTO's Better Buildings Alliance initiated a High Performance Rooftop Unit Challenge to "urge manufacturers to build and deliver innovative, competitively priced, energy-saving rooftop units" that, among other specifications, much achieve an integrated energy efficiency ratio (IEER) of 18.0 or

[49] Environmental Protection Agency (EPA). 2014. "Unit Shipment Data." ENERGY STAR. Available at: www.energystar.gov/index.cfm?c=partners.unit_shipment_data
[50] Davis, Matt. 2014. "NH Thermal RECs: What you need to know." Ground Energy Support. July 17, 2014. Available at: groundenergysupport.com/wp/nh-thermal-recs-need-know/
[51] Press release from GEO, August 4, 2014, available: www.geoexchange.org/news/regional-news/massachusetts-news/landmark-legislation-promotes-renewable-heating-cooling-massachusetts/
[52] Available equipment found via the Consortium for Energy Efficiency (CEE) / Air-Conditioning, Heating, and Refrigeration (AHRI) directory at: www.ceedirectory.org/; available equipment changes on a regular basis. ENERGY STAR specifications for air-source HPs and central A/Cs is available at: www.energystar.gov/index.cfm?c=airsrc_heat.pr_crit_as_heat_pumps.

more.[53] The challenge began in 2011, and in May 2012, Daikin-McQuay became the first manufacturer to meet the challenge and Carrier soon followed suit. Lennox, 7AC Technologies, and Rheem are all participating in the challenge. By comparison the current ENERGY STAR minimum performance level is 11.7 EER and 11.8 IEER.[54] While IEER is typically within 10% of the EER, products that meet the challenge specifications are able to boost the IEER to as much as 50% greater than the EER by focusing on part-load performance improvement (while still increasing EER to greater than 13).[55]

- **Condensing RTUs** – Adoption of condensing heat exchangers for gas-fired RTUs has lagged behind condensing technology integration in residential and other select commercial heating applications. Disposal of acidic condensate is challenging due to the required freeze protection in sub-32°F environments and routing through sanitary sewer as disposal through rooftop storm drains is unacceptable due to acidity concerns. Select manufacturers, including Munters, Reznor, Engineered Air, and Modine, have started offering products for dedicated-outdoor air system applications (DOAS).[56] Sales of condensing RTU's may be limited to select regions where the climate justifies the investment and the gas savings in winter greatly overcome any fan energy penalty from the secondary heat exchanger in all seasons.

Additionally, the market is growing for other more proven technologies, such as variable speed compressors and fans, energy recovery ventilators (ERVs), and energy management and advanced control systems for residential and light commercial applications.

3.4 Barriers to Achieving Energy Savings

3.4.1 Technical Barriers

Table 3-1 lists some of the key technical barriers to achieving BTO energy savings goals.

[53] RTU Challenge information available at: www4.eere.energy.gov/alliance/activities/technology-solutions-teams/space-conditioning/rtu and further detail on the specifications is available at: apps1.eere.energy.gov/buildings/publications/pdfs/alliances/cbea_rtu_spec_long.pdf

[54] ENERGY STAR minimum specifications for Light Commercial Heating and Cooling equipment V2.0 with greater than 65kBtu/hr capacity, effective May 1, 2010, available: www.energystar.gov/index.cfm?c=lchvac.pr_crit_lchvac.

[55] Comparison of EER and IEER is based on review of ENERGY STAR qualified products with greater than 65 kBtu/hr capacity. Note that it is not possible to convert between these two metrics – comparison is for illustrative purposes only. Data accessed September 12, 2014, available: www.energystar.gov/productfinder/product/certified-light-commercial-hvac/results

[56] Kerr, Ryan. "Condensing Rooftop Units: The Road to Market." Gas Technology Institute. (May 21, 2013) Accessed September 2, 2014: www.centerpointenergy.com/staticfiles/CNP/Common/SiteAssets/doc/CondensingRooftopUnit_RyanKerr.pdf

Table 3-1: Technical Barriers

Barrier	Description
Sustained performance	As complexity of systems increase in order to achieve greater performance, degradation (fouling, mechanical wear, etc.) can have a greater impact. Systems must be designed to maintain performance throughout the life of the product and alert the customer if maintenance is required to return to optimal performance levels.
Whole-system efficiency	Much effort is focused on improving standard energy metrics for the primary heating or cooling equipment in an HVAC system (e.g., SEER, AFUE); however, energy use and cost of the entire system is equally dependent on performance of distribution systems, auxiliary components, and controls. For example, a high-efficiency water-cooled chiller losses some of its potential energy savings if the distribution system, cooling tower, and control scheme is not designed and controlled appropriately. Future R&D should emphasize lossless (or near lossless) distribution systems and controls that ensure that space conditioning only occurs where and when needed.
Few available incremental improvements	Traditional vapor-compression systems and fossil-fuel-based heating systems have not changed substantially in decades. Recent R&D efforts have helped tackle much of the low-hanging efficiency fruit (e.g., ultra-high efficiency mini split systems, condensing boilers, etc.). To make substantial leaps forward in efficiency, new approaches must be considered that radically deviate from traditional equipment.

In addition to high level barriers, HVAC R&D efforts run into many technology-specific barriers; Figure 3-5 lists a selection of these technology-specific barriers.

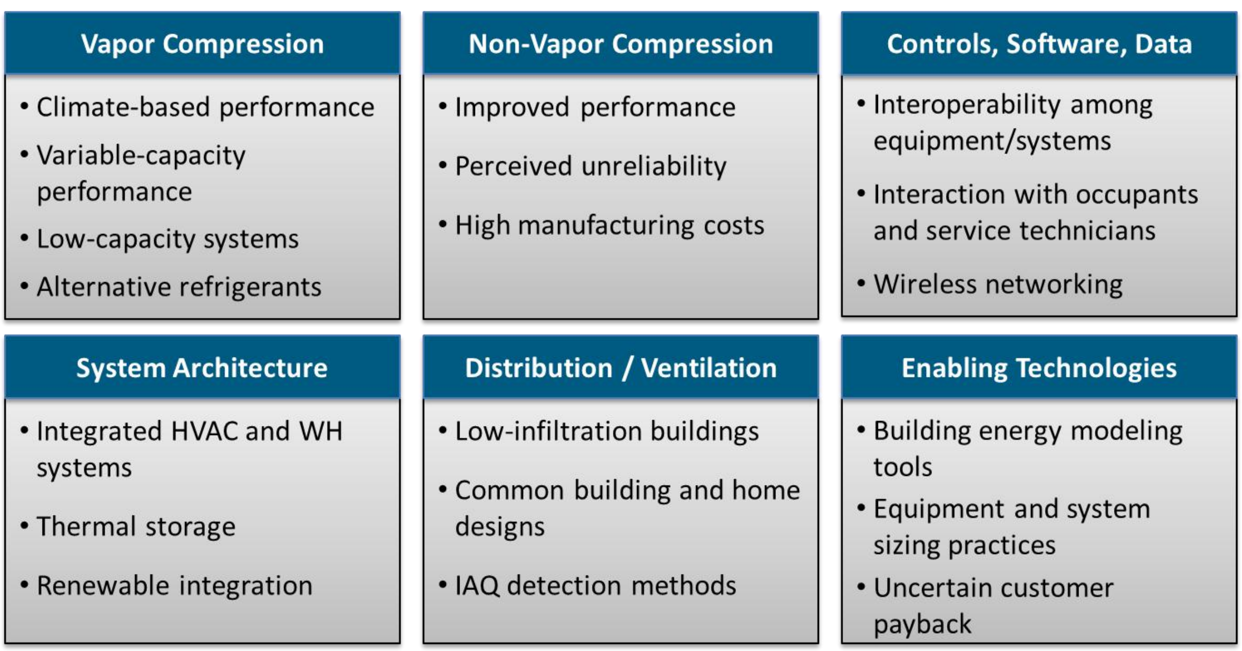


Figure 3-5: Technology-specific barriers to achieving energy savings

3.4.2 Market Barriers

While this roadmap aims to support BTO energy savings goals through technical R&D, researchers must be aware of market challenges as well as technical challenges in order for their work to be successful in the marketplace. Table 3-2 lists some of the key technical barriers to achieving BTO energy savings goals.

Table 3-2: Market Barriers

Barrier	Description
Cost effectiveness	As with any high-efficiency equipment, cost is of utmost importance in order to assure market acceptance. Cost is particularly important for HVAC equipment, which is already a very large investment for most home and building owners. Consumers who make purchase decisions based primarily on first cost will not be likely candidates for purchase of higher cost equipment that can save them on operating costs. While part of this barrier can be overcome through greater consumer education and awareness of energy benefits, first-cost barriers must also be addressed directly.
Market acceptance	Many new HVAC market entrants require additional resources and/or knowledge for safe, correct installation. Primary causes include heavier and larger equipment; mounting structures that are incompatible with existing ductwork, requiring new roof curb adapters (for RTUs); and complex installation procedures that require participation by multiple trades. Without knowledge of, and experience with, these challenges with new equipment, installers are hesitant to sell such systems.
Energy is not the sole driving factor for sales	New equipment purchases generally occur at the time of equipment failure and therefore consumers are limited to products that are readily through their local distributor or HVAC contractor. In selecting new equipment, comfort, noise level, and other non-energy factors constitute the greatest influence on buying decisions. High efficiency equipment must incorporate these additional benefits in order to succeed through rapid market adoption.

4 Research & Development Roadmap

This roadmap contains four sections below:

- *Central Themes* – Summary of themes that emerged during roadmap development that carry common threads through many (if not all) of the prioritized initiatives
- *Direct-Impact Technologies* – Summary of findings on direct-impact technology initiatives, including P-Tool results
- *Enabling Technologies* – Summary of findings on enabling technology initiatives

The sections do not specifically distinguish between the various end-use and market sector subcategories of HVAC technologies; where relevant, the initiatives are labeled with their associated subcategory. The various high priority initiatives, detailed below, broadly cover the various sectors and market sectors as applicable, though this roadmap makes no specific effort to cover each category evenly.

4.1 Central Themes

The Roadmap Forum in Atlanta, in addition to providing valuable input on specific initiatives, also uncovered some key themes that undercut much of the work that BTO may pursue. The themes in Figure 4-1 provide general context to the individual roadmap activities listed in the proceeding sections.

Qualitative Stakeholder Feedback Themes:

Build in tolerance for system misapplication

- Systems should accommodate oversizing or be designed so it is not possible
- Built-in tolerance enables more plug-and-play solutions

Recognize that each home is a unique system

- Existing home vary dramatically in how they operate
- Detailed data on past HVAC operations can advise future purchasing decisions

Envision what retrofits look like in 2050

- Having a vision of future building trends will improve HVAC system design
- Retrofitting buildings in the future may embody different steps than today

Emphasize peak demand mitigation

- Peak-shifting storage technologies provide value to consumers & utilities alike
- Smart equipment for automatic demand response and predictive control

Optimize components for alternative refrigerant systems

- Efficiency improvements should be targeted when redesigning components
- Proactive pursuit of technology advances will accelerate refrigerant transition

Figure 4-1: Key qualitative themes

In addition, analysis of the stakeholder inputs provided insights into key content categories that the stakeholders emphasized, including:

- **Renewables integration** – Components, equipment, systems, and design tools that enable integration of renewable energy sources with HVAC system, generally with the renewable source as the primary thermal source.
    - *Related initiatives:* solar thermal heating and cooling (sorption), phase-change materials (PCMs) for energy storage, waste-heat capture, photovoltaic (PV) powered unitary A/C.
- **Holistic, system-level analysis and integrated energy systems** – Components, equipment, modeling tools, and enabling technologies that facilitate cascading energy to/from HVAC to another building process to reduce overall building consumption.
    - *Related initiatives:* Integrated systems, single-compressor-based home “energy wall,” systems-based analysis and design tools, and design guides.

- **Proper system design, installation, and operation** – Hardware, software, design tools, and other enabling technologies that more readily incorporate high-efficiency HVAC products in high-performance buildings.
  - *Related initiatives:* Enabling design tools, commissioning, proper operations and maintenance (O&M), contractor-focused approaches to performance improvements.
- **Optimal ventilation and indoor air quality (IAQ)** – Technologies that ensure proper IAQ through improved methods and techniques.
  - *Related initiatives:* IAQ monitors, sensors, and controls, humidity management, demand ventilation.
- **Advanced HPs** – Technologies and designs that improve the current state of unitary HVAC equipment.
  - *Related initiatives*: improved controls, self-commissioning, on-board storage, variable speed equipment, non-vapor-compression based systems.
- **Region-specific designs –** Technologies and system designs that specialize in a specific climate (cold-climate, hot-dry, hot-humid), instead of traditional, one-size-fits-all-regions approaches.
  - *Related initiatives:* Cold-climate heat pumps (CCHPs), separated latent and sensible load management for humid climates.
- **Adapting to alternative refrigerants** – component and equipment design, safety protocols (including sensors, fault detection and diagnostics [FDD]), contractor tools, etc. that proactively help facilitate and accelerate the industry's transition to refrigerants with lower global warming potential (GWP).
  - **Note:** these initiatives are not covered in this roadmap. For additional information, see the BTO Refrigerants Roadmap, published in 2011. BTO is currently preparing an update to this roadmap.[57]

4.2 Direct-Impact Technology Initiatives

Table 4-1 lists the 10 direct-impact initiatives that were scrutinized in greatest detail during roadmap development. This subsections that follow detail the Tier 1 initiatives (6 of 10) in greater detail, with Tier 2 initiatives described further in Appendix C – Tier 2 Initiatives.

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[57] "Research and Development Roadmap for Next-Generation Low-Global Warming Potential Refrigerants," Report by Navigant Consulting, Inc., for BTO, July 2011, available: energy.gov/sites/prod/files/2014/07/f17/next_generation_refrigerants_roadmap.pdf

Table 4-1: Prioritized List of Direct-Impact R&D Initiatives

ID	Activity/Initiative	Topic	Tier
1	Develop a direct-current (DC)-powered HVAC system to utilize DC power from a solar PV system without inverter losses and facilitate microgrid integration	Renewables & Storage	1
3	Develop and evaluate new techniques for separate sensible and latent control and quantify the energy savings	AC/HP	1
4	Develop techniques to raise HP performance (all fuels) at low-ambient temperature; consider elimination of defrost (or frost buildup) and backup heat sources to improve the application of CCHPs	AC/HP	1
5	Develop electrochemical compression systems	AC/HP	1
8	Develop methods, technologies, and other innovations to easily integrate seasonal energy storage into residential and commercial projects	Renewables & Storage	1
10	Investigate new absorption pairs, compact heat exchangers, and other material advances to reduce the cost of absorption systems for res/light commercial	AC/HP	1
20	Develop hybrid systems to combine mechanical and natural ventilation techniques aka mixed-mode conditioning or integrated window ventilation	Ventilation & Humidity	2
33	Research strategies to improve ground-source heat pump (GHP) ground-loop cost and performance; also consider siting, installation, and modeling to reduce costs	AC/HP	2
35	Develop alternative non-solid-state, non-thermally activated HPs with suitable efficiency, cost, and performance compared to next generation HVAC equipment	AC/HP	2
52	Develop solid-state cooling systems	AC/HP	2

Figure 4-2 shows the savings potential values from the P-Tool for all nine initiatives.

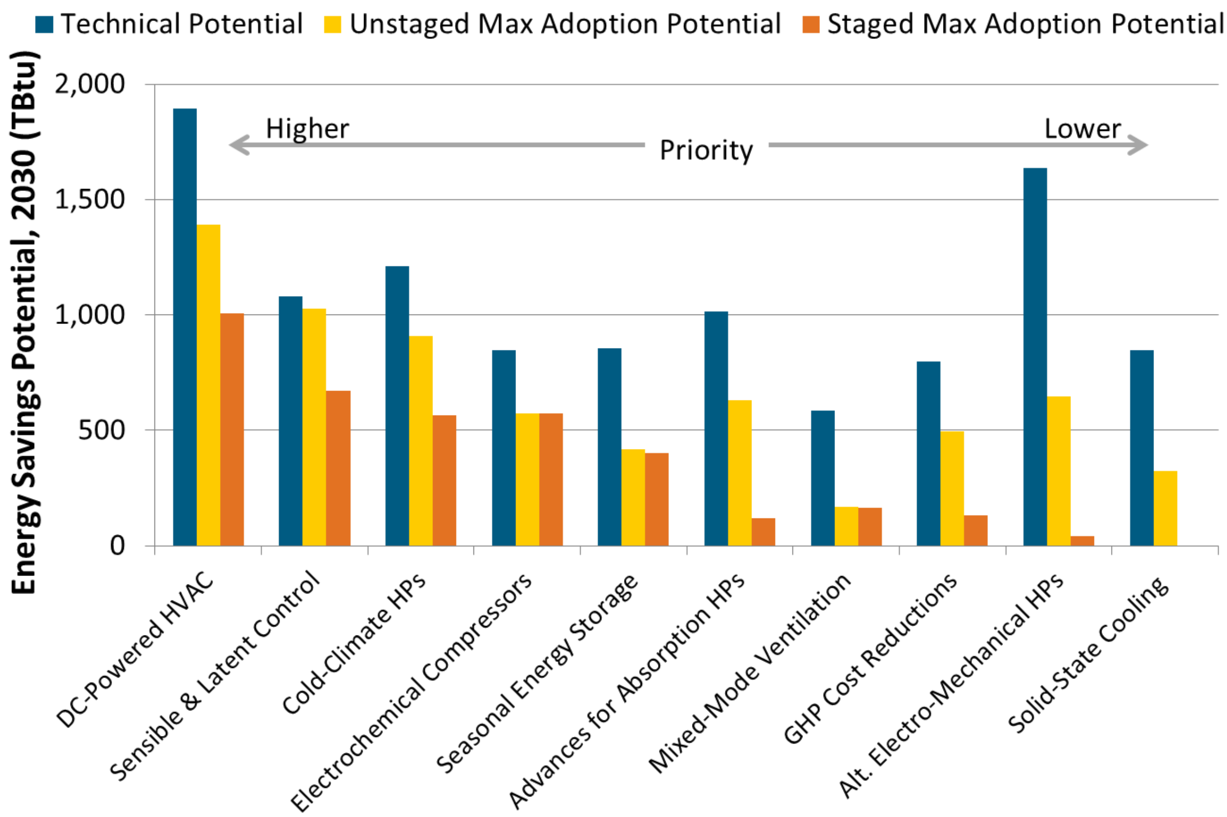


Figure 4-2: Direct-impact initiative savings potential

Table 4-2 summarizes the building sectors and fuel sources used in the P-Tool analysis for each initiative and provides the resulting technical and staged savings potential. We assume that the applicable market for each technology is only the portion of the market using the same fuel as the target technology, i.e. we do not account for fuel switching opportunities.

Table 4-2: Summary of Inputs to P-Tool Analysis for Direct-Impact Initiatives

ID	Activity/Initiative	Applicable Sectors	Applicable Fuel Sources	Technical Potential (TBtu)	Staged Max Adoption Potential (TBtu)
1	DC-Powered HVAC for Solar PV Integration	Residential	Electricity	1,894	1,008
3	Separate Sensible and Latent Heat Management	Residential, Commercial	Electricity	1,082	673
4	CCHPs	Residential, Commercial	Electricity, Natural Gas	1,211	566
5	Electrochemical Compressor Systems	Residential, Commercial	Electricity	848	572
8	Seasonal Energy Storage	Residential, Commercial	Electricity, Natural Gas	867	400

ID	Activity/Initiative	Applicable Sectors	Applicable Fuel Sources	Technical Potential (TBtu)	Staged Max Adoption Potential (TBtu)
10	Material/Refrigerant Advances for Absorption Systems	Residential, Commercial	Natural Gas	1,017	121
20	Hybrid, Mixed-Mode Ventilation	Commercial	Electricity	597	165
33	GHP Cost Reductions	Residential, Commercial	Electricity	799	133
35	Alternative Non-Solid-State, Non-Thermally Activated HPs	Residential, Commercial	Electricity	1,636	42
52	Solid-State Cooling	Residential, Commercial	Electricity	848	0

The following subsections provide detail on the Tier 1 direct-impact initiatives.

4.2.1 (ID #1) DC-Powered HVAC for Solar PV Integration

Initiative: *Develop a direct-current (DC)-powered HVAC system to utilize DC power from a solar PV system without inverter losses and facilitate microgrid integration*

Under this initiative, BTO would investigate the potential benefits of direct-current (DC)-enabled HVAC technologies for microgrid integration, and if promising, support the development of prototype systems. With the increasing popularity of customer-sited electrical generation and/or storage systems, building owners are evaluating the benefits of semi-autonomous electrical systems, known as microgrids, for use as either system back-up or as a cost-savings measure.

Because solar PV, fuel cells, and battery systems operate with DC power, buildings with microgrids attempt to minimize the conversion losses (e.g., AC-to-DC and DC-to-AC) between generation, storage, and end usage. As one of the largest building loads, HVAC systems designed for DC-power would reduce the losses normally incurred from conversion of PV and battery electricity to AC power. Additionally, the systems would significantly offset the building's peak electrical demand since the peak solar resource generally coincides with highest space cooling demands. DC-enabled HVAC systems already exist for specialized markets such as telecommunications, electronics, and transportation systems, but limited options exist for building-scale HVAC systems. If successfully developed, DC-enabled HVAC systems could facilitate greater integration of distributed energy resources, including renewable generating sources, and reduce transmission, distribution, and conversion losses throughout the current electricity infrastructure.

Table 4-3 describes the technical challenges facing DC-powered HVAC systems.

Table 4-3: Technical Challenges

Technical Barriers	Description
Limited improvement for efficiency metrics	The current test procedures and efficiency metrics (e.g., SEER, HSPF) would not account for the potential source energy savings of a DC-enabled HVAC system.
Limited microgrid technologies to date	DC-enabled HVAC systems would rely on on-site electricity storage and other microgrid technologies that have limited adoption and availability for residential and light-commercial buildings outside of specialized off-grid or transportation applications.
Lack of trained workforce	HVAC technicians and system designers would require training to design, install, and service DC-powered systems and components.
Potential stakeholder conflicts	Technologies that incorporate on-site HVAC, electrical, and utility infrastructure require the coordination of many stakeholders who do not typically interact on most residential and light-commercial projects.

Figure 4-3 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

Near-Term (1–3 Yrs.)	Mid-Term (3–5 Yrs.)	Long-Term (5–7 Yrs.)
Action Items: » Research the benefits of DC-enabled HVAC systems » Conduct market analysis of other microgrid technologies required for DC-enabled HVAC » Develop and test prototype DC-enabled HVAC systems	**Action Items:** » Conduct limited field evaluation of DC-enabled HVAC system & microgrid on sample home(s) » Develop R&D and commercialization roadmap of necessary activities to address remaining technology, market, and policy gaps » Support advances in other microgrid technologies by researchers & industry groups	**Action Items:** » If market and technology look favorable, develop market-ready prototype and conduct year-long field studies » Support the development of alternative test procedures and rating schemes for DC-enabled HVAC systems
Milestones: » Publish findings » Go/no-go decision for prototype development » Go/no-go decision for field demonstration	**Milestones:** » Publish findings and roadmap » Go/no-go decision on further development and commercialization	**Milestones:** » Publish findings » Adoption of alternative test procedures

Figure 4-3: Timeline & milestones – DC-powered HVAC for solar PV integration

This initiative will develop, test, and identify the role of DC-enabled HVAC systems as part of larger microgrid energy systems for residential and commercial buildings. Table 4-4 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-4: Market Impact – DC-Powered HVAC for Solar PV Integration

Relevant Market Barrier	Initiative's Impact
Limited DC-power equipment available outside of ductless mini-splits	Develops prototype systems for common equipment types.
Limited performance information to date	Documents performance and efficiency during field testing in relevant applications for industry evaluation in microgrid systems.
Limited focus on HVAC systems in future on-site energy and microgrid systems	Published studies, roadmap, and field tests of prototypes will highlight HVAC's role in future distributed energy and microgrid systems.

Table 4-5 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-5: Stakeholder Involvement – DC-Powered HVAC for Solar PV Integration

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » HVAC equipment and electrical component manufacturers
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design » National laboratories – survey design, end-use knowledge/support » Surveying organizations – survey design, recruitment, execution
Deployment	» BTO – Residential & Commercial Buildings » HVAC equipment and electrical component manufacturers » Building designers (residential and commercial) » Industry organizations » Utilities
Codes and standards	» BTO – Appliance & Equipment Standards » National laboratories » HVAC equipment and electrical component manufacturers » Industry organizations

4.2.2 (ID #3) Separate Sensible and Latent Heat Management

Initiative: *Develop and evaluate techniques for separate sensible and latent control and quantify the energy savings*

Under this initiative, BTO would support the development and demonstration of technologies that incorporate or enable sensible and latent control (also referred to as "separate sensible and latent cooling" [SSLC]) for A/C systems, and promote their usage through field demonstrations, test procedure development, and other activities. Traditional A/C systems remove both sensible heat (temperature) and latent heat (the energy required to evaporate or condense water) from supply air to create comfortable conditions for building occupants. While this practice serves most cooling applications effectively, high-efficiency buildings with low conduction and infiltration loads or those in humid climates require a higher percentage of latent cooling capacity.

Several strategies and techniques are available to achieve SSLC including: using multiple vapor-compression cycles (e.g., dehumidifier), lowering supply airflow for moisture removal, solid or liquid desiccant materials that capture water vapor, selectively permeable membranes that transport water molecules across their surface, heat pipes, and other methods. Through the Building America program, BTO has supported simulation and field studies to identify low-energy dehumidification strategies and identify best practices for the building industry. While many of these technologies are available today as add-on components, incorporating these technologies into packaged solutions can lower the installation cost/ complexity, especially for retrofit applications, and better coordinate the control of sensible and latent cooling mechanisms.

Table 4-6 describes the technical challenges facing separate sensible and latent heat management.

Table 4-6: Technical Challenges

Technical Barriers	Description
Limited latent cooling capacity of conventional systems	Traditional cooling systems may cycle off before latent loads are satisfied, especially if they are oversized for the space.
Uncertain or unfamiliar design practices	Especially for residential systems, climate regions that have not experienced humidity issues will need to address latent loads due to tighter building envelopes.
Increased energy consumption	Traditional system using separate dehumidification or overcool/reheat techniques consume considerable energy.
Separate installation or ducting	If the dehumidification components are not integrated into the main HVAC system, space constraints and installation complexity may hinder applications, especially for retrofit systems.

Figure 4-4 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring these technologies to market.

Near-Term (1–3 Yrs.)	Mid-Term (3–5 Yrs.)	Long-Term (5–7 Yrs.)
Action Items: » Support research and product development on alternative methods to control sensible & latent loads independently » Conduct laboratory testing on promising strategies when integrated with standard HVAC systems » Develop field test plan for different building types, climate regions, etc. » Finalize product development for testing	**Action Items:** » Conduct field analyses with different building types, climate regions, HVAC system designs, etc. » Revise product design based on field experience » Support development of test procedures & metrics for independent sensible and latent cooling systems » Develop go-to-market commercialization strategy	**Action Items:** » Conduct additional case studies with early-adopters and develop best practices
Milestones: » Publish findings from research and product development » Go/no-go decision for field tests	**Milestones:** » Publish findings from field studies » Go/no-go decision for commercialization activities	**Milestones:** » Publish best practices guidelines

Figure 4-4: Timeline & milestones – separate sensible and latent heat management

This initiative will develop and demonstrate technologies that provide independent control of sensible and latent cooling loads for improved energy consumption in high-performance buildings and humid environments. Table 4-7 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-7: Market Impact – Separate Sensible and Latent Heat Management

Relevant Market Barrier	Initiative's Impact
Limited ability to manage occupant comfort for humidity and temperature	Addressing sensible and latent loads independently allows more direct control of indoor environmental conditions, improving occupant comfort.
Limited design guidelines	Conducting field demonstrations and developing best practice guidelines assists HVAC contractors to design and install advanced systems.
Low-energy operation	Using advanced dehumidification approaches in conjunction with standard vapor-compression sensible cooling systems reduces overall consumption to provide indoor comfort.
Separate installation or ducting	Designing an integrated solution for common HVAC system designs reduces installation complexity.

Table 4-8 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-8: Stakeholder Involvement – Separate Sensible and Latent Heat Management

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » HVAC equipment manufacturers » Building designers
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design » National laboratories – survey design, end-use knowledge/support » Surveying organizations – survey design, recruitment, execution
Deployment	» BTO – Residential & Commercial Buildings » HVAC equipment manufacturers » Building designers (residential and commercial) » Industry organizations
Codes and Standards	» BTO – Appliance & Equipment Standards » National laboratories » HVAC equipment and electrical component manufacturers » Industry organizations

4.2.3 (ID #4) Cold-Climate Heat Pumps

Initiative: *Develop techniques to raise heat pump performance (all fuels) at low-ambient temperature; consider elimination of defrost (or frost buildup) and backup heat sources to improve the application of CCHPs*

Traditionally, vapor-compression HPs have had limited use in colder climates due to decreasing heating capacity and COP as outdoor temperatures decrease because of the increased temperature lift across the compressor. BTO has supported the development of CCHPs through several projects highlighted in Section 1.2.3, above. Under this initiative, BTO would continue the development of CCHPs using vapor-compression and alternative cycles to both improve the performance and economics for residential and light-commercial applications.

During low-temperature operation, back-up electric resistance heating would compensate for this performance drop at the expense of efficiency, such that the HP provided minimal benefit over a standard A/C with an electric or gas furnace. In recent years, manufacturers have designed electrically-driven HPs for cold-climate operation through the use of multi-stage, variable-speed, or booster compressors, advanced refrigerant management, improved defrost control, alternative refrigerants, and other features. Additionally, HPs using absorption and other thermally activated cycles can achieve higher efficiencies in low temperature operation than conventional fuel-fired furnaces and boilers.

Table 4-9 describes the technical challenges facing CCHPs.

Table 4-9: Technical Challenges

Technical Barriers	Description
Limited past success	Previous CCHP designs provided underwhelming performance, efficiency, and reliability, leading to poor market adoption.
Sizing equipment for cooling rather than heating	Even for colder regions, contractors often size HPs for cooling loads.
Low supply air temperatures	Past heat pumps provided space heating at lower temperatures than gas-fired products.
Natural gas as a lower cost heating fuel	For both electric and gas HPs, low natural gas prices increase payback periods compared to furnaces and boilers, lowering the attractiveness of advanced technologies.

Figure 4-5 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring these technologies to market.

Near-Term (1–3 Yrs.)	Mid-Term (3–5 Yrs.)	Long-Term (5–7 Yrs.)
Action Items: » Continue to support the development of components, strategies, and systems that improve HP performance in cold climates » Develop a standardized rating scheme to distinguish a CCHP from a standard model » Develop field demonstration test plan for promising technologies	**Action Items:** » Solicit candidate field demonstration sites and conduct pre-installation analysis » Conduct field demonstrations for various building designs, climate regions, etc., over and entire heating and cooling season » Develop best practice guidelines for sizing, installation, O&M, etc.	**Action Items:** » None expected
Milestones: » Publish research findings and developments » Industry recognition of "cold-climate performance" » Go/no-go decision for field demonstrations	**Milestones:** » Publish findings from field demonstrations » Publish best practice guidelines	**Milestones:** » None expected

Figure 4-5: Timeline & milestones – CCHP

This initiative will develop and demonstrate advanced components, controls, and systems for CCHPs using both electricity and natural gas. Table 4-10 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-10: Market Impact – CCHP

Relevant Market Barrier	Initiative's Impact
Diminished thermal output, reliability, and efficiency at low ambient temperatures	Incorporating advanced compressor designs, defrost techniques, and other features improves the performance of CCHPs beyond previous products.
Poor market perception of technology	Conducting field demonstrations throughout heating-dominated climates verifies improved performance of current CCHPs.

Relevant Market Barrier	Initiative's Impact
Contractor experience and sizing practices	Developing and distributing the demonstration case studies and best practice guidelines assists contractors with proper design, installation, and maintenance of CCHPs.

Table 4-11 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-11: Stakeholder Involvement – CCHPs

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » HVAC equipment manufacturers
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design » National laboratories – survey design, end-use knowledge/support » Surveying organizations – survey design, recruitment, execution
Deployment	» BTO – Residential & Commercial Buildings » HVAC equipment manufacturers » Building designers (residential and commercial) » Industry organizations
Codes and Standards	» BTO – Appliance & Equipment Standards » National laboratories » HVAC equipment and electrical component manufacturers » Industry organizations

4.2.4 (ID #5) Electrochemical Compression Systems

Initiative: *Develop electrochemical compression systems*

HPs using electrochemical compressors could offer scalable operation, utilize low-GWP refrigerants, and operate with minimal noise, but their success ultimately depends on cycle efficiency and cost compared to electromechanical compressors. BTO is currently supporting research at Xergy Inc. to develop electrochemical compressors for HPWHs. Under this initiative, BTO would support the development of electrochemical compressors for space cooling and space heating applications following successive initial research for water heating. After laboratory demonstration, BTO should conduct field studies in a variety of real-world conditions to understand how electrochemical HVAC systems perform overtime relative to conventional A/C and HP systems.

In place of a motor-driven compressor, electrochemical compressors raise the pressure of a hydrogen working fluid using a proton exchange membrane and electricity source. The pressurized hydrogen gas combines with water, ammonia, or another refrigerant, raising its pressure and driving the combined working fluid through condenser, expansion valve, and evaporator in a standard Rankine vapor-compression cycle.

Table 4-12 describes the technical challenges facing electrochemical compression systems.

Table 4-12: Technical Challenges

Technical Barriers	Description
Unproven compressor technology	Electrochemical compressors have been studied for hydrogen vehicle refueling and other applications, but have not been developed yet for building applications.
Uncertain performance once combined as an entire HVAC system	Even with high compressor efficiencies, working fluid selection and inefficiencies in the rest of the vapor-compression cycle may limit system efficiencies.
Requirements for high reliability	Alternative compressor technologies must meet or exceed the reliability of conventional compressors, which typically last the full 10–15 year operating life of vapor-compression equipment.

Figure 4-6 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

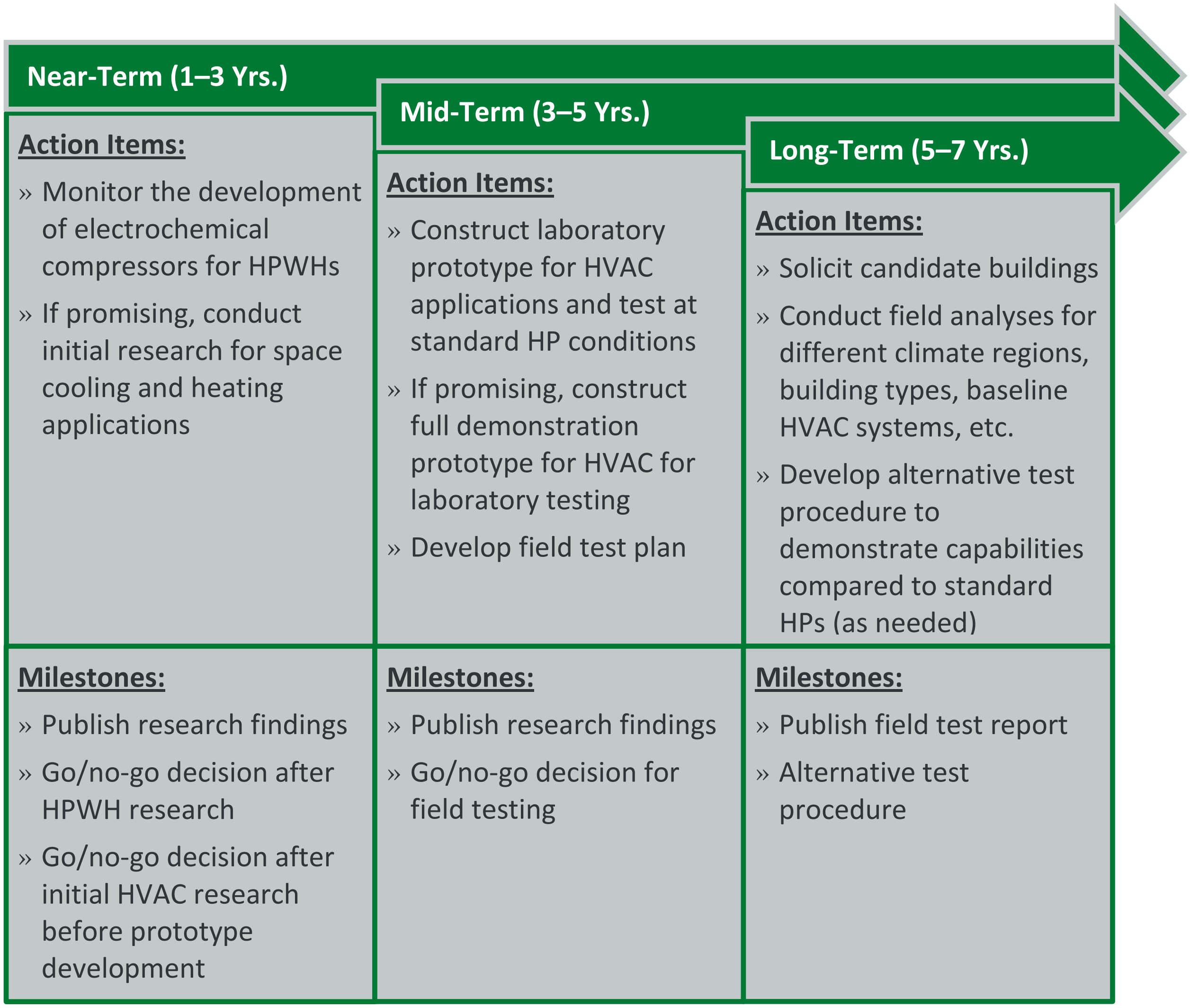


Figure 4-6: Timeline & milestones – electrochemical compression systems

If the water heating research suggests acceptable efficiency, longevity, and cost, this initiative develop an initial prototype and demonstrate a novel electrochemical compressor for HP applications. Table 4-13 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-13: Market Impact – Electrochemical Compression Systems

Relevant Market Barrier	Initiative's Impact
Current product availability	If successful, this initiative would introduce HVAC products using electrochemical compressors.
Refrigerant phase out	As high-GWP refrigerants phase out of the HVAC industry, electrochemical compressors may have more attractive economics and efficiency compared to new vapor-compression systems.
Equipment noise	Without an electromechanical compressor, electrochemical-based systems may have significantly reduced noise.

Table 4-14 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-14: Stakeholder Involvement – Electrochemical Compression Systems

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » HVAC equipment manufacturers
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design » National laboratories – survey design, end-use knowledge/support » Surveying organizations – survey design, recruitment, execution
Codes and Standards	» BTO – Appliance & Equipment Standards » National laboratories » HVAC equipment manufacturers » Industry organizations

4.2.5 (ID #8) Seasonal Thermal Energy Storage

Initiative: *Develop methods, technologies, and other innovations to easily integrate seasonal energy storage into residential and commercial projects*

Under this initiative, BTO would analyze the potential for residential and light-commercial seasonal thermal energy storage (STES) systems in cold climates through a life-cycle cost analysis using data collected from existing systems and support research into modular or standardized STES system designs that facilitate integration with new and existing buildings.

In Northern climates, building operators can use the seasonally available solar thermal energy for HVAC applications through STES. These systems collect the low-cost thermal energy in the summer and store it for use in the winter, offsetting a portion of the space and water heating energy use. System designers have used several STES variations including: highly insulated water tanks, open-loop aquifer systems, or closed-loop borehole systems where a GHP operates more efficiently as the increased soil temperature lowers the required temperature lift during the heating season. While more popular in Europe, Canada, and other areas, STES has not achieved wide usage in the U.S. due to high first cost, the availability of low-cost natural gas, system complexity, unfamiliarity of designers, size/space considerations, etc. Additionally, borehole systems that would heat the ground in the summer would reduce the cooling efficiency of GHPs. Nevertheless, STES has significant potential both energy savings and greater integration of renewable resources for heating-dominated climates.

Table 4-18 describes the technical challenges facing seasonal thermal energy storage.

Table 4-15: Technical Challenges

Technical Barriers	Description
Site-specific project designs	Each project requires a complex engineering design to account for available storage area, required space and water heating load, available solar or geothermal resources, distribution system, and other considerations.
Uncertain cost and payback projections	Because of the complex design, building owners and system designers are not able to conduct a quick analysis to determine whether STES is a viable option for their projects.
Limited designer and contractor experience	Since so few projects have occurred in the U.S., building designers, contractors, and other industry professionals have limited awareness or experience with STES projects.
Customer preferences for furnaces	Most STES projects use water as the heat transfer and storage fluid, which poses added complexity with air-side distribution systems designed for furnaces.

Figure 4-8 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

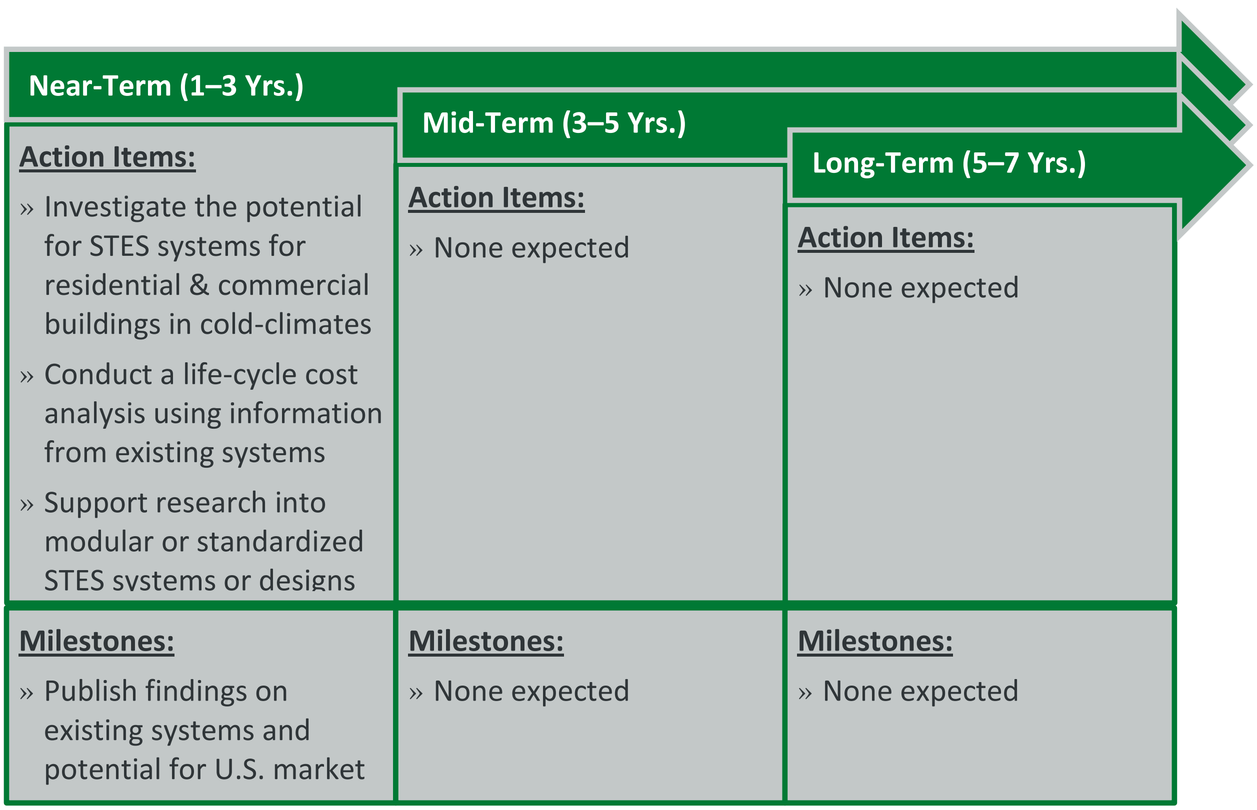


Figure 4-7: Timeline & milestones – STES

If the technology shows success, develop further, conduct field demonstrations, and design best practice guidelines.

This initiative would analyze the potential for STES to cost effectively utilize renewable heating energy in the U.S. market and support the development of lower cost, more standardized systems. Table 4-16 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-16: Market Impact – STES

Relevant Market Barrier	Initiative's Impact
Uncertain lifecycle costs and benefits	Examining past projects in Europe, Japan, and Canada provides the energy consumption and economic data to develop more detailed estimates for the U.S.
Limited U.S. application	Analyzing the potential market and available resources for STES and compiling best practices from other countries enables building designers to investigate STES for their projects.
Complex system designs	Developing standardized storage mechanisms, controls, and system designs allows less complex and costly installations.

Table 4-20 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-17: Stakeholder Involvement – STES

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » Building designers » BTO – Residential & Commercial Buildings

4.2.6 (ID #10) Material/Refrigerant Advances for Absorption Systems

Initiative: *Investigate new absorption pairs, compact heat exchangers, and other material advances to reduce the cost of absorption systems for res/light commercial*

Under this initiative, BTO would continue the development of alternative working pairs and improved designs for absorber, generator, condenser, and other components that allow higher efficiencies, more compact designs, and/or can lead to lower-cost absorption systems.

Absorption systems utilize thermal energy to drive a heat-pump cycle where a refrigerant is cyclically absorbed and desorbed from a secondary fluid. Depending on the configuration, absorption HPs can be designed as heating-only, cooling-only, or reversible (both heating and cooling). Although cooling efficiencies are typically less than those for vapor-compression systems, absorption HPs offer large potential energy and cost savings, especially for heating-dominated climates. BTO has supported the development of absorption HPs for HVAC and water heating applications for several decades and manufacturers now offer products, but absorption systems still carry a substantial cost premium related to their size, weight, and operational requirements. Several efforts are underway to address barriers to increased adoption of absorption systems, including:

- Developing benign refrigerant pairs or introducing a third working fluid that inhibits the crystallization process[58]
- Using microchannel[59] or membranes absorbers and desorbers[60,61]
- Constructing the various chambers and channels of the absorption HP by building up thin metal sheets[62]
- Utilizing a cascade reverse-osmosis system to separate the refrigerant-absorbent pair in place of a thermal generator.[63, 64]

Table 4-18 describes the technical challenges and market barriers facing absorption HPs.

Table 4-18: Technical Challenges

Technical Barriers	Description
Increased size and weight over conventional systems	The size and weight of absorption systems are higher than conventional systems due to the added material to prevent corrosion, maintain sealed vacuum conditions, and achieve the necessary heat and mass transfer.
Working fluid operating risks	Current working fluids of absorption HPs pose operating risks related to their toxicity (e.g., ammonia) and crystallization (e.g., LiBr). If the temperature of the LiBr solution deviates from a narrow range, the solution may crystallize and render the chiller inoperable.
High complexity and first cost relative to payback	Cost of current generation of absorption products carry a substantial cost premium relative to gas furnaces and boilers are only offered in limited set of modular sizes.
Customer preference for furnaces	Because most residential and light-commercial buildings use air-side distribution systems, absorption systems would require an additional blower when replacing furnaces.

[58] Wang et al. 2011. “State-of-the-Art Review on Crystallization Control Technologies for Water / LiBr Absorption Heat Pumps.” Oak Ridge National Laboratory. April 2011.
[59] TeGrotenhuis et al. 2012. Performance of a Compact Absorption Heat Pump Containing Microchannel Absorber Components.” International Refrigeration and Air Conditioning Conference. July 2012.
[60] Isfahani and Moghaddam. 2013. “Absorption Characteristics of Lithium Bromide (LiBr) Solution Constrained by Superhydrophobic Nanofibrous Structures.” University of Florida. International Journal of Heat and Mass Transfer. April 23, 2013.
[61] Isfahani et al. 2014. “Physics of Lithium Bromide (LiBr) Solution Dewatering through Vapor Venting Membranes.” University of Florida. International Journal of Multiphase Flow. Vol. 58. January 2014.
[62] Determan and Garimella. 2010. “A Microscale Monolithic Absorption Heat Pump.” Georgia Institute of Technology. International Refrigeration and Air Conditioning Conference. July 2010.
[63] Ricci, Stephen. 2013. Research Leader. Battelle Memorial Institute. Personal Communication with Jim Young of Navigant. October 2013.
[64] Saunders, Keri. 2012. “Battelle Memorial Institute – Cascade Reverse Osmosis Air Conditioning System.” ARPA-e. February 2012.

Figure 4-8 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring these technologies to market.

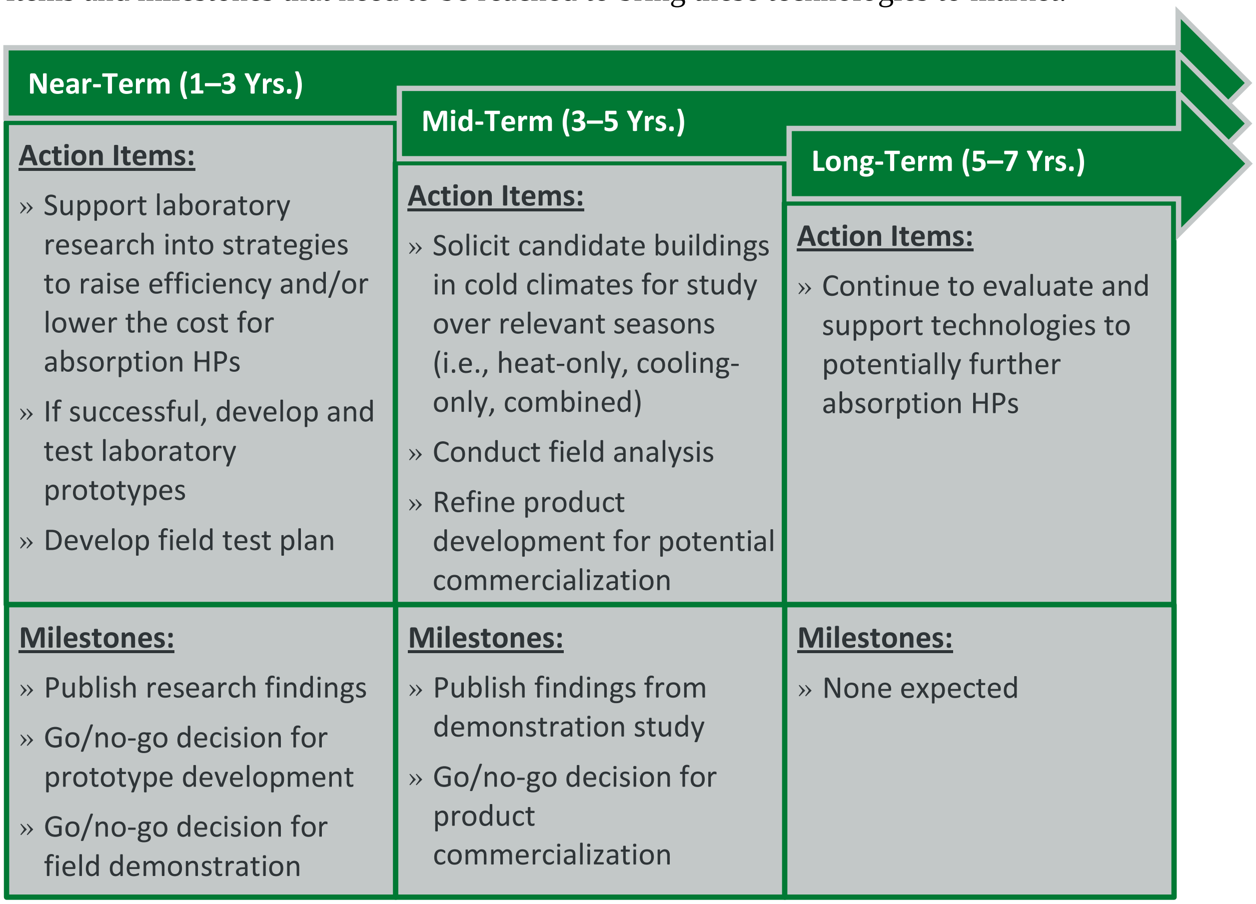


Figure 4-8: Timeline & milestones – advances for absorption systems

This initiative will support the development of components, designs, or alternative strategies that improve the cost effectiveness of absorption HPs by lowering their cost, improving their energy efficiency, or reducing other barriers. Table 4-19 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-19: Market Impact – Advances for Absorption Systems

Relevant Market Barrier	Initiative's Impact
Limited lifecycle cost advantage over conventional systems	Developing lower cost or higher efficiency systems improves the payback of absorption systems, for both heating and cooling.
Minimal market acceptance and awareness to date	Publishing the results and lessons learned from field studies helps building designers, contractors, and building owners understand the benefits and operations of absorption systems.
Safety and operational risks	Utilizing systems with alternative working fluids reduces the barriers posed by building codes that limit the siting of absorption systems.

Table 4-20 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-20: Stakeholder Involvement – Advances for Absorption Systems

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » HVAC equipment and electrical component manufacturers
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design » National laboratories – survey design, end-use knowledge/support » Surveying organizations – survey design, recruitment, execution
Deployment	» HVAC equipment and electrical component manufacturers » Building designers (residential and commercial) » Industry organizations » Utilities
Codes and standards	» BTO – Appliance & Equipment Standards » HVAC equipment and electrical component manufacturers » Industry organizations

4.2.7 Tier Two Direct-Impact Initiatives

The following initiatives, though not articulated in-depth like the Tier 1 initiatives, are also valuable opportunities to further BTO energy savings goals and should be considered for future action. Table 4-21 lists a short title for each Tier 2 direct-impact initiative. Appendix C – Tier 2 Initiatives provides detailed descriptions of each initiative.

Table 4-21: Tier 2 Direct Impact Initiatives

ID	Tier 2 Direct-Impact Initiative(Short Title)	Research Area	ID	Tier 2 Direct-Impact Initiative(Short Title)	Research Area
11	Air Cleaning Methods and Testing Procedures	Ventilation & Humidity	13	Reliable, Cost-Effective FDD Strategies	FDD Controls
14	Next Generation Window A/Cs	AC/HP	18	Ducting Diagnostics	FDD Controls
19	Small Scale CHP + Cooling (Tri-generation)	CHP, Electricity, Heat Recovery	20	Hybrid, Mixed-Mode Ventilation	Ventilation & Humidity

ID	Tier 2 Direct-Impact Initiative(Short Title)	Research Area	ID	Tier 2 Direct-Impact Initiative(Short Title)	Research Area
21	Residential Zoning Technologies	Zoning Distribution	22	Next Generation Chillers	AC/HP
23	Solar Thermal HPs	Renewables & Storage	24	Microclimate Space Conditioning	Zoning Distribution
25	High Performance Packaged HVAC	AC/HP	26	Nano-fluids HVAC Research	Refrigerants
30	On-Board HVAC Energy Storage	Renewables & Storage	33	GHP Cost Reductions	AC/HP
35	Alternative Non-Solid-State, Non-Thermally Activated HPs	AC/HP	36	HVAC Waste-Heat Recovery Engine	CHP, Electricity, Heat Recovery
37	Improved Economizer Reliability	Ventilation & Humidity	40	Aerosol Duct Sealing Improvements	Zoning Distribution
45	Thermoelectrically Enhanced Subcoolers	Component Development	48	Cost Effective PCM-based Energy Storage	Renewables & Storage
49	Solar Ventilation Pre-Heating	Renewables & Storage	51	Hybrid Adsorption-Vapor-Compression HP Storage	Renewables & Storage
52	Solid-State Cooling	AC/HP	54	Low-Cost Chilled Water Storage	Renewables & Storage
55	Thermal-chemical Energy Storage	Renewables & Storage			

4.3 Roadmap for Enabling Technology R&D Initiatives

As discussed in Section 1.3, enabling initiatives indirectly improve energy efficiency of HVAC and other building systems. Through the roadmap development process, some key enabling initiatives surfaced that can be key drivers of energy savings. This section details the Tier 1 initiatives (4 of 10) in this category. Table 4-22 lists all 10 enabling initiatives identified during roadmap development.

Table 4-22: Prioritized List of Enabling R&D Initiatives

ID	Activity/Initiative	Topic	Tier
2	Collect data and conduct analysis on the pervasiveness and energy impacts of incorrect system commissioning, poor installation, incorrect operation, and poor (and good) maintenance of HVAC systems in commercial buildings	Installation O&M	1
6	Develop and demonstrate an open-source, open-architecture platform that enables smart grid connectivity for demand response, and communication of energy, operational and financial transactions between HVAC and other building systems	FDD Controls	1
7	Develop a low-cost sensor network and control scheme where every surface, critical object, and occupant has a sensor	FDD Controls	1
9	Develop standardized methods of built-in data acquisition and data storage for sizing and equipment selection purposes at end of life	Tools & Software	1
12	Develop and demonstrate renewable-integrated district heating, cooling, and power systems for a community, campus, or city.	District Systems	2
15	Develop an open-source building automation system to drive innovation	Tools & Software	2
16	Develop a standardized building metric to incorporate energy, health, etc.	Analysis, Education, Demonstration	2
17	Investigate the prevalence of simultaneous heating and cooling in buildings and evaluate energy recovery and improved thermal distribution methods	Zoning Distribution	2
27	Develop energy analysis tools for the homeowner to conduct a simple economic analysis before purchasing new equipment (focus on existing buildings) – Homeowner focus	Tools & Software	2

ID	Activity/Initiative	Topic	Tier
28	Compile the lessons learned from NREL's high performance buildings database and develop tools, guides to educate the industry	Tools & Software	2

Enabling initiatives do not have a specific energy savings tied to them. Instead, they provide pathways to achieving energy savings via the systems they support or relate to. Enabling initiatives therefore cannot be compared on a quantitative basis with the direct-impact initiatives. BTO therefore cannot quantitatively compare them with other potential R&D investments, across all potential building technology opportunities, using the P-Tool. The following subsections document the details of recommended enabling initiatives, including barriers, action items, and stakeholder roles and responsibilities.

4.3.1 (ID #2) Impacts of Poor Installation, Commissioning, or O&M

Initiative: *Collect data and conduct analysis on the pervasiveness and energy impacts of incorrect system commissioning, poor installation, incorrect operation, and improper maintenance of HVAC in residential and commercial buildings*

Under this initiative, BTO would provide an independent assessment of the benefits of quality installation, commissioning, and maintenance practices through a comprehensive study of available literature, and field studies of different building categories throughout the country. Even the most efficient equipment and best designed system become losing investments for the building owner if the system does not operate to its intended capabilities due to poor installation or maintenance practices. Because the energy savings of these practices often go unnoticed and are difficult to predict, the results of these studies would provide quantification for the energy and financial benefits of proper practices and better demonstrate their value to contractors and consumers.

For HVAC equipment and systems to operate as expected, proper installation and commissioning at startup, followed by proper operation and regular maintenance is essential. Such practices help assure the building's HVAC system provides indoor comfort with high performance, efficiency, and safety. To reduce the frequency of underperforming systems, various stakeholders in the HVAC industry including contractors, equipment manufacturers, industry experts, utilities, and building owners have developed specifications and certification programs for installation, commissioning, and maintenance, (e.g., ACCA Standard 5 QI, ASHRAE/ACCA Standard 180, others). Nevertheless, additional research is needed to quantify the expected benefits of proper installation, commissioning, and maintenance in order to develop the business case for these non-equipment measures.

As part of this initiative, BTO would seek to quantify the impacts of poor installation, commissioning, and maintenance practices, identify the underlying causes of system malfunction, and outline the expected benefits of proper practices with regard to:

- Energy efficiency

- Energy consumption and peak demand
- System capacity
- Control of temperature, humidity, and occupant comfort
- Excess noise and vibration
- Occupant and technician safety
- IAQ and occupant health
- Equipment lifetime
- Operational downtime and callbacks
- Others.

While many of the same issues occur across building categories, equipment types, climate regions, this study should aim for wide representation of the U.S. building stock. Providing detailed results for various HVAC system designs, building operations, and climates can enable contractors and building owners to make better decisions for their specific application.

Figure 4-9 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

Near-Term (1–3 Yrs.)	Mid-Term (3–5 Yrs.)	Long-Term (5–7 Yrs.)
Action Items: » Conduct comprehensive literature review » Design field research plan » Solicit candidate buildings » Qualify and select participating buildings » Conduct field analyses	**Action Items:** » Continue field research » Develop best practices guide and financial tools based on research	**Action Items:** » Conduct follow-up research on initial field study buildings to understand changes over time
Milestones: » Publish findings of literature review » Achieve participant list with wide representation of building stock » Publish findings of field studies	**Milestones:** » Publish findings of field studies and analysis tools » Go/no-go decision for follow on research of diagnostic tools	**Milestones:** » Publish findings

Figure 4-9: Timeline & milestones – impacts of poor installation, commissioning, or O&M

Building on findings of earlier research, technology developers may create diagnostic tools to address the identified issues. At such a time, we recommend BTO consider and evaluate technologies, tools, or strategies that can better identify and diagnose the presence and severity of poor practices. If promising, BTO should conduct field analysis with diagnostic tools and support their commercialization.

This initiative will provide the underlying data that can enable building operators, contractors, and service providers to more accurately predict the energy, operational, and financial benefits of proper practices, and increase their adoption. Table 4-23 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-23: Market Impact – Impacts of Poor Installation, Commissioning, or O&M

Relevant Market Barrier	Initiative's Impact
Low awareness of benefits	Published findings can increase contractor, building operator, and customer awareness for the value of proper system practices.
Apprehension/skepticism	By providing independent field analysis, the initiative provides an unbiased study of the expected energy and financial costs of avoiding proper practices.
Short-term financial outlook	Laying out the long-term costs and benefits through an easy-to-use financial tool helps industry professionals explain the benefits to customers.
Time pressures during extreme conditions	By understanding how improper practices lower system performance and reduce customer satisfaction, contractors can improve their training on quality installation and maintenance practices.

Table 4-24 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-24: Stakeholder Involvement – Impacts of Poor Installation, Commissioning, O&M

Tasks	Key Stakeholder Roles and Responsibilities
Program management	» National laboratories » BTO and/or BTO subcontractor
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design » National laboratories – survey design, end-use knowledge/support » Manufacturers/Controls Vendors – equipment data mining » Surveying organizations – survey design, recruitment, execution
Deployment	» BTO » EPA » Industry organizations

4.3.2 (ID #6) Open-Source Smart Grid Connectivity Platform

Initiative: *Develop and demonstrate an open-source, open-architecture platform that enables smart grid connectivity for demand response, and communication of energy, operational, and financial transactions between HVAC and other building systems*

Recent developments in a variety of building subsystems have provided increased monitoring and control capabilities. With the gains, residential and commercial buildings can potentially achieve significant energy and/or cost savings through coordinated control and automation both within the building, and through interaction with the smart grid. BTO has supported the development of transactional network controls through various projects at Pacific Northwest National Laboratory (PNNL), ORNL, Lawrence Berkeley National Laboratory (LBNL), and other organizations. Under this initiative, BTO would continue to develop software and hardware solutions to facilitate the centralized interaction of building systems with smart grid capabilities and conduct field demonstrations for promising technologies.

An open-platform controls network allows environmental or equipment-monitoring sensors for a particular component to relay information in a hierarchal structure to a central control system for use by the other building components. By connecting the monitoring and control infrastructure of these various systems, a centralized network platform can quantify the financial cost and benefits of specific operations against time-of-use rates, demand response rates, and other smart grid tools. Knowing the cost and benefit of potential actions, the system can then develop strategies to achieve energy or cost objectives through transactions between systems or the building. For example, this transactional network can adjust the scheduling of multiple HVAC units and other end-uses to remain below a peak demand limit, demand response limit, or other strategies to achieve building owners' comfort and performance goals in an energy-efficient and cost-effective manner.[65]

Larger commercial buildings can already use these features as part of complex building management systems, but more work is needed to bring these capabilities to residential and light-commercial buildings. Using an open-platform, manufacturers and service providers can more readily incorporate their products into a simplified control network and enable plug-and-play interoperability, lowering project cost.

Figure 4-10 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

[65] Nutaro et al. 2014. "An Inexpensive Retrofit Technology for Reducing Peak Power Demand in Small and Medium Commercial Buildings." Oak Ridge National Laboratory. 3rd International High Performance Buildings Conference at Purdue, July 2014.

	Near-Term (1–3 Yrs.)	Mid-Term (3–5 Yrs.)	Long-Term (5–7 Yrs.)
Action Items:	» Develop controls platform for residential and light-commercial buildings » Develop low-cost, wireless, plug-and-play sensors for the network » Explore and investigate different use cases and control strategies through simulation analysis » Develop field test plan » Solicit candidate buildings, utilities, and other partners	» Conduct field analyses of different building types, HVAC systems, and other building systems » Revise controls platform based on findings » Develop go-to-market commercialization strategy	» Conduct additional field studies w/early-adopters » Promote the usage of transactional network applications to manufacturers, industry organizations, utilities, etc. » License technology and systems to, manufacturers, service providers, etc.
Milestones:	» Publish findings of simulation studies » Field-ready sensors and controls systems » Go/no-go decision for field tests	» Publish findings from field tests » Commercialization strategy	» Increased adoption for buildings and high performance products » Publish best practices from field studies

Figure 4-10: Timeline & milestones – open-source smart grid connectivity platform

This initiative will develop the necessary hardware, software, control algorithms, and communications protocols to enable more efficient and lower cost operations for residential and commercial buildings through improved system control and grid-enabled capabilities. Table 4-25 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-25: Market Impact – Open-Source Smart Grid Connectivity Platform

Relevant Market Barrier	Initiative's Impact
Hardware and software are difficult to configure	Plug-and-play capabilities reduce installation complexity and commissioning time
Sensor networks and control systems are expensive and difficult to power	Developing a low-cost, distributed, and self-powered suite of sensors can lower first cost premium and complexity for projects
Poor communication among building systems	Common communications protocols and controllers enable interaction of various building systems.

Relevant Market Barrier	Initiative's Impact
Uncertain financial payback and other benefits	Performing numerous field studies provides independent verification of the expected benefits for building owners and service providers.

Table 4-26 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-26: Stakeholder Involvement – Open-Source Smart Grid Connectivity Platform

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » Sensors and controls manufacturers » Utilities
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design » National laboratories – survey design, end-use knowledge/support » Surveying organizations – survey design, recruitment, execution
Deployment	» BTO » Sensors and controls manufacturers » Equipment and building systems manufacturers » Service providers » Utilities

4.3.3 (ID #7) Low-Cost Sensor Networks

Initiative: *Develop a low-cost sensor network and control scheme where every surface, critical object, and occupant, has a sensor*

Under this initiative, BTO would continue to support this effort through development of the sensor platforms themselves, developing control methodologies using more refined data, analyzing the potential energy savings, and working to demonstrate their utility for various HVAC systems.

Traditional HVAC systems rely on simple temperature and humidity sensors in one or more thermostats to control the amount of space heating, cooling, and ventilation delivered to the thermal zone. The decreasing cost and improved capabilities of wireless electronics offer the potential for more universal sensor communication networks that could improve HVAC control methodologies through improved occupancy sensing and other strategies. DOE's Sensors and Controls program, the European Union's (EU) Tibucon project[66], and other research organizations have funded research on low-cost, self-powered wireless sensor platforms that could facilitate non-invasive monitoring system throughout the building. These efforts would support the initiative outlined in Section 4.3.2 by decreasing the cost of deploying monitoring

[66]Tibucon Project. 2014. Available: www.tibucon.eu/

sensors across a building and developing a suite of networked sensors that easily integrates and communicates with the hierarchal transactional platform. Additionally, the information gathered from the sensor network can not only improve HVAC performance and efficiency, but also facilitate other building subsystems, such as lighting.

Figure 4-11 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

Near-Term (1–3 Yrs.)	Mid-Term (3–5 Yrs.)	Long-Term (5–7 Yrs.)
Action Items: » Identify requirements on low-cost, lightweight, low-power temperature, humidity, light, and other sensors » Conduct research to integrate sensing capabilities into a single package » Develop self-generating components capable of harvesting energy from various building environments » Investigate control algorithms to utilize multiple sensors » Perform simulations to understand the potential energy savings	**Action Items:** » Integrate energy-harvesting capabilities with sensors » Conduct laboratory testing with HVAC system using advanced sensors and control strategy » Incorporate plug-and-play capabilities into a package of sensors and central communication system » Conduct reliability and lifetime testing » Develop field test plan	**Action Items:** » Solicit candidate buildings, utilities, and other partners » Conduct field analyses of different building types, HVAC systems, and other building systems » Revise sensors and controls platform based on findings » Develop go-to-market commercialization strategy
Milestones: » Publish findings of sensor breakthroughs » Publish findings of simulation studies	**Milestones:** » Publish findings of lab demonstrations » Go/no-go decision for larger field demonstration	**Milestones:** » Publish findings from field demonstrations » Commercialization strategy

Figure 4-11: Timeline & milestones – low-cost sensor networks

This initiative will improve the occupant comfort and energy efficiency for residential and commercial buildings by enabling more data collection for precise environmental control. Table 4-27 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-27: Market Impact – Low-Cost Sensor Networks

Relevant Market Barrier	Initiative's Impact
Imprecise building controls	Improved sensors placed throughout the building allow for more precise control of temperature, humidity, lighting, etc.
Complex sensor installation	By featuring wireless and energy-harvesting capabilities, the sensors would not require physical connections to a central communications system.
Energy supply issues	In place of an electrical line or replaceable battery, energy-harvesting systems coupled with rechargeable batteries would provide the sensor's power needs.
Uncertain payback and benefits	Performing laboratory and field studies provides detailed estimates for the potential energy savings and comfort benefits of the networked wireless sensors.

Table 4-28 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-28: Stakeholder Involvement – Low-Cost Sensor Networks

Tasks	Key Stakeholder Roles and Responsibilities
R&D	» National laboratories » Academic researchers » Sensors manufacturers
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design, execution » National laboratories – survey design, end-use knowledge/support
Deployment	» BTO » Sensors and controls manufacturers » Equipment and building systems manufacturers

4.3.4 (ID #9) Built-in Data Acquisition for Equipment Sizing and Selection

Initiative: *Develop standardized methods of built-in data acquisition and data storage for sizing and equipment selection purposes at end of life*

Under this initiative, BTO would conduct research to determine operating patterns of optimal and improperly sized packaged HVAC systems and develop FDD algorithms to facilitate proper sizing during equipment replacement cycles.

For many residential and light commercial buildings, system designers rely on ACCA Manual J (Residential), ACCA Manual N (Light-Commercial) and other specifications to size space conditioning systems appropriately. Improperly sized equipment can lead to excessive energy consumption, shortened equipment life, poor humidity control, and other issues that affect system performance. Because equipment manufacturers only offer a limited number of capacities, contractors commonly oversize A/C equipment to reduce the chance of callbacks during the hottest days of the year or by simply installing the replacement unit with the same capacity as the existing equipment. Because the load characteristics within the building may have changed due to weatherization upgrades or changes in activity, the required system size may be significantly different than during the original installation of the older equipment.

Monitoring the operation of equipment nearing the end of its operating life could improve system sizing practices during eventual replacement. An on-board data acquisition and storage system could record the A/C's operating runtimes, electricity demand patterns (or signature), and other key information. The technician could download the data from a diagnostic port or other method and use software to determine whether the system was correctly sized for the building before ordering the replacement system. BTO should support the development of on-board sizing analysis features as part of a larger FDD system for packaged and split-system A/Cs.

Figure 4-11 outlines an approximate timeline for this initiative and identifies the major action items and milestones that need to be reached to bring this technology to market.

Near-Term (1–3 Yrs.)	Mid-Term (3–5 Yrs.)	Long-Term (5–7 Yrs.)
Action Items: » Perform a laboratory and limited field study to characterize the operating signature of proper and improperly sized systems » Conduct research on gathered data to develop predictive algorithms and analysis software » Integrate sizing software with common FDD systems and perform lab & field studies to determine effectiveness	**Action Items:** » Work with equipment & controls manufacturers, service providers, etc. to incorporate algorithms into their service offerings » Develop operating protocol for service technicians in conjunction w/industry stakeholders » Support the inclusion of this feature in high-performance specifications	**Action Items:** » None expected
Milestones: » Publish findings » Go/no-go decision on further work based on demonstrated success	**Milestones:** » Publish findings » Standard feature of manufacturer's on-board FDD package	**Milestones:** » None expected

Figure 4-12: Timeline & milestones – built-in data acquisition for equipment sizing & selection

While the effects will not be realized for 10–15 years when equipment using the feature is due for replacement, this initiative will help improve the performance, energy efficiency, and occupant comfort of packaged HVAC systems over the life of residential and commercial buildings. Table 4-29 identifies the impact that the initiative will have on key market barriers in the HVAC industry.

Table 4-29: Market Impact – Built-in Data Acquisition for Equipment Sizing & Selection

Relevant Market Barrier	Initiative's Impact
Imprecise equipment sizing methods	By measuring actual equipment operation against a sizing algorithm, technicians would know the proper size for the building.
Lengthy equipment sizing methods	Automated systems would reduce the time to determine proper equipment size and thereby reduce equipment replacement costs.
Ownership changes lose information on efficiency upgrades	Because current methods require knowledge of insulation ratings, infiltration rates, and other features which may be lost during ownership changes, automated sizing practices would incorporate any efficiency upgrades made by the previous owners.

Table 4-28 identifies the critical stakeholders for implementing the initiative and discusses each stakeholder's role.

Table 4-30: Stakeholder Involvement – Built-in Data Acquisition for Equipment Sizing & Selection

Tasks	Key Stakeholder Roles and Responsibilities
R&D, laboratory studies	» National laboratories » Academic researchers » Equipment and sensors manufacturers
Field studies, data analysis, and report publication	» Independent research firms – protocols, field test design, execution » National laboratories – survey design, end-use knowledge/support » Equipment and sensors manufacturers
Deployment	» BTO » Equipment and sensors manufacturers » Industry organizations

4.3.5 Tier Two Enabling Technology Initiatives

The following initiatives, though not articulated in-depth like the Tier 1 initiatives, are also valuable opportunities to further BTO energy savings goals and should be considered for future action. Table 4-31 lists a short title for each Tier 2 enabling technology initiative. Appendix C – Tier 2 Initiatives provides detailed descriptions of each initiative.

Table 4-31: Tier 2 Enabling Technology Initiatives

ID	Tier 2 Enabling Tech Initiative (Short Title)	Research Area	ID	Tier 2 Enabling Tech Initiative (Short Title)	Research Area
12	Renewable-Integrated District Thermal/Power Systems	Installation O&M	15	Open-Source Building Automation	FDD Controls
16	Standardized Building Metrics for Energy, Health, more	FDD Controls	17	Simultaneous Heating/Cooling Savings Opportunities	Tools & Software
27	Simple Economic Analysis Tools for Homeowners	District Systems	28	High Performance Buildings Database Lessons Learned	Tools & Software
29	Universal Communications Protocols	Analysis, Education, Demonstration	31	Standardized Fault Definitions and Communication Protocols	Zoning Distribution
32	Low-Cost IAQ Monitors	Tools & Software	34	Comprehensive FDD Benefits Study	Tools & Software
38	Universal Communications Port for On-Board Diagnostics	FDD Controls	39	Systems-Level HVAC Design Guides	FDD Controls
41	Open-Source Continuous Commissioning Tools	FDD Controls	42	Non-Vapor-Compression Energy Conservation Metrics and Test Procedures	FDD Controls
43	Optimization of Predictive Scheduling and Controls	FDD Controls	44	Simple Contractor Modeling Tools	Tools & Software
46	Automated Bathroom/Kitchen Exhaust Fans	Tools & Software	47	Occupant Monitoring Algorithms	Test Procedures, Standards, Policy
50	RTU Teardown Analysis for Size/Weight Savings Opportunities	FDD Controls	53	Customer-Focused Energy Dashboards	Tools & Software
56	Opportunities for Reductions in Refrigerant Leakage and Charge Size	Ventilation & Humidity	57	Dry-Cooling in Lieu of Evaporative Condensers	FDD Controls

4.4 HVAC Technolgy R&D Portfolio

The prioritized initiatives in this roadmap cover a broad selection of HVAC technology topic areas, including many that specifically support BTO's current target technology areas (see Section 1.2.1, above). Table 4-32 shows the Tier 1 and Tier 2 initiatives that support BTO's target areas (initiative titles abbreviated for brevity, and repeated where appropriate).

Table 4-32: Direct-Impact Initiatives that Support BTO Target Areas

Target Area	Aligned Initiatives	Notes
Cold-Climate Heat Pumps	• ID#4 Low-Ambient Temperature HP Performance (all fuels)	Helps support BTO efforts in developing regional (climate-customized) HVAC solutions
Natural Gas-Driven Heat Pumps (inc. multifunction products)	• ID#10 Material/Refrigerant Advances for Absorption Systems	Dovetails well with existing gas-fired heat pump research
Non-Vapor-Compression Heat Pumps	• ID#35 Alternative Non-Solid-State, Non-Thermally Activated HPs • ID#52 Solid-State Cooling	Initiatives emphasize long-term, innovative solutions that aim to leap-frog current technologies
Advanced Vapor-Compression Technologies	• ID#5 Electrochemical Compressor Systems • ID#26 Nano-fluids HVAC Research • ID#45 Thermoelectrically-Enhanced Subcoolers	Initiatives emphasize component research for incremental improvements to existing architectures

During roadmap development, BTO issued a Notice of Intent for "Building Energy Efficiency Frontiers & Innovations Technologies (BENEFIT) – 2015."[67] BENEFIT targets many of the topics discussed in this roadmap, categorized broadly around two of the BTO target areas, but addressing many others:[68]

- **Non-vapor-compression HVAC technologies**, under which BTO looks to support development of both natural gas and electric technologies in support of a "non-vapor-compression HVAC future," such as absorption, adsorption, magnetocaloric, thermoelectric, and many more (see footnote for reference to the notice for details.)
- **Advanced vapor-compression HVAC technologies**, under which BTO points to many topic areas covered in this roadmap, such as advanced vapor-compression compressors,

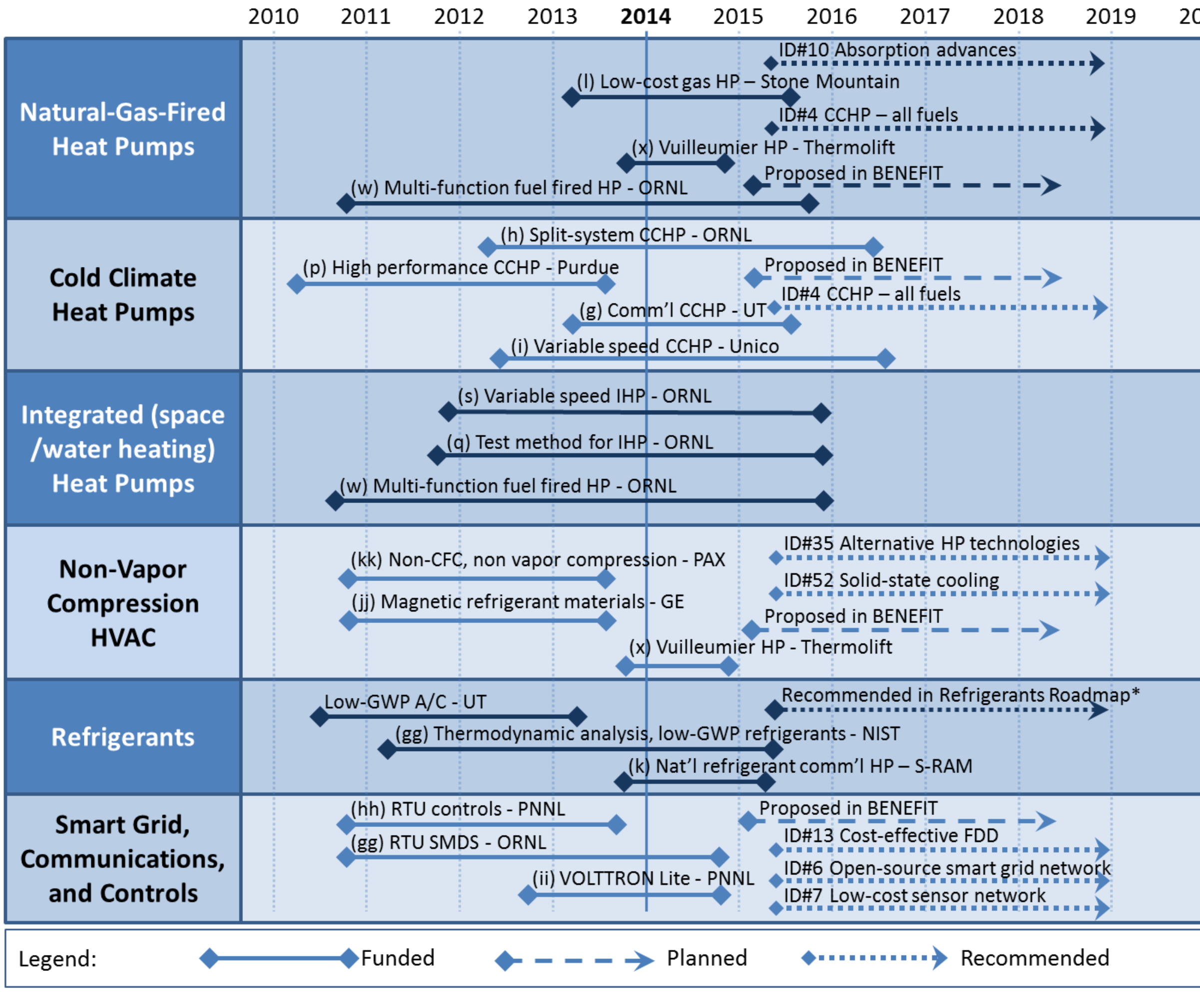
[67] Notice of Intent DE-FOA-0001180 concerning Funding Opportunity Announcement (FOA) DE-FOA-0001166 for BENEFIT, posted September 8, 2014, additional information available: energy.gov/eere/buildings/articles/notice-intent-building-energy-efficiency-frontier-innovations-technologies-de-foa

[68] BENEFIT Notice of Intent available at: https://eere-exchange.energy.gov/FileContent.aspx?FileID=b56f1e40-64dc-43c1-981a-8add0c03d12f

regional HVAC solutions, SSLC, CCHP (cost reduction only), hybrid technologies that may include non-vapor-compression elements that enable SSLC A/C Systems, HVAC systems with embedded energy and thermal storage.

Many of the recommended roadmap initiatives are outside the domain of BTO’s specific technology targets but nevertheless address other important barriers. For example, the enabling initiatives that address installation, O&M, sizing, and distribution systems all address issues raised by stakeholders during development of this roadmap. These initiatives are mixed in throughout both Tier 1 and Tier 2 initiatives with those initiatives that do address key BTO focus areas. Four of the top 10 initiatives are enabling technologies that address these barriers.

Many initiatives in this roadmap align with BTO’s recent and current HVAC R&D activities, as Figure 4-13 shows. While this figure does not cover all past or current BTO R&D activities, it does illustrate how the roadmap initiatives continue BTO research in six key areas. The majority of initiatives in the selected areas are direct-impact initiatives, but the Smart Grid, Communications, and Controls category includes enabling technologies due to the software focus of the category. For additional information on each initiative in the figure, see sections 1.2.2 to 1.2.5. For additional information on the roadmap initiatives, refer to section 4.2 or 4.3 as appropriate.



Notes: the letters in parenthesis identify the corresponding table entry in these sections
*Refrigerants roadmap, currently in development, covers refrigerant-related R&D (see section 1.2 for scope of this roadmap)

Figure 4-13: Example HVAC projects in BTO's portfolio by focus area

While Figure 4-13 does not comprehensively cover BTO's R&D landscape, thermal energy storage and SSLC are two categories notably absent from the list. The figure excludes both technology categories because they are areas in which BTO has invested less historically. Nevertheless, BTO research has contributed valuable advances in these areas, for example:

- NREL's development of DEVap (desiccant-enhanced evaporative cooling) technology[69] (SSLC)
- University of Maryland's winning entry in the 2011–2012 "Max Tech and Beyond"[70] competition (SSLC)
- NREL modeling and analysis work for packaged A/C storage systems[71] (thermal energy storage).

[69] E. Kozubal, J. Woods, and R. Judkoff, "Development and Analysis of Desiccant Enhanced Evaporative Air Conditioner Prototype." NREL Technical Report (April 2012) Accessed September 29, 2014: www.nrel.gov/docs/fy12osti/54755.pdf

[70] Max Tech and Beyond team page for "Separate Sensible and Latent Cooling System: 2011-2012." Accessed September 29, 2014: maxtechandbeyond.lbl.gov/team/team-umdsslcac

While these areas have had limited BTO investment in the past, both BENEFIT and the roadmap initiatives point to greater investment in the future. The roadmap includes recommended top-tier initiatives in both of these categories: ID#3 Separate Sensible and Latent Heat Management, and ID#8 Seasonal Thermal-Energy Storage.

Although the initiatives discussed in this roadmap are programmatically independent and require no critical-path sequencing, some activities in this roadmap may benefit from coordinated scheduling. For example, Enabling initiatives ID#7 Low-Cost Sensor Networks and ID#32 Low-Cost IAQ Monitors, may be able to leverage knowledge between the two initiatives for efficient use of resources. Direct initiatives that use similar components may also benefit, such as initiatives ID#19 Small-Scale CHP plus Cooling and ID#36 HVAC Waste-Heat Recovery Engine. The objectives may differ between the projects, but collaboration could advance each technology further. BTO should consider opportunities for worthwhile collaboration when incorporating new projects in its R&D portfolio.

For each initiative, BTO should also consider how the research could serve as a stepping stone in related building systems, such as water heating and refrigeration. Conversely, water heating or refrigeration research could also benefit the development of more complex HVAC systems. For example, as heat pump water heaters become more common, they become increasingly relevant to HVAC research. The potential to leverage inter-related benefits may impact how BTO considers sequencing various HVAC initiatives relative to water heating or refrigeration initiatives.

[71] F. Kung, M. Deru, and E. Bonnema. "Evaluation Framework and Analysis for Thermal Energy Storage Integrated with Packaged Air Conditioning." NREL Technical Report (October 2013) Accessed September 29, 2014: www.nrel.gov/docs/fy14osti/60415.pdf

5 Appendix A – HVAC Forum Summary Report

US Department of Energy's Research and Development Roadmap for Heating, Ventilation, and Air Conditioning Technologies
June 17, 2014

Stakeholder Forum Summary – ASHRAE Headquarters, Atlanta, GA

Summary

On June 17, 2014, Navigant Consulting, Inc., on behalf of the U.S. Department of Energy's (DOE) Building Technologies Office (BTO), hosted a stakeholder forum to identify research and development (R&D) needs and critical knowledge gaps related to heating, ventilation, and air conditioning (HVAC) technologies. This forum covered HVAC equipment, distribution systems, and enabling technologies such as advanced controls and sensors. BTO is the office through which DOE funds research to support emerging building technologies and they aim to reduce total building-related energy consumption by 50% by the year 2030. In HVAC technologies, BTO has specifically set a target of 20% energy savings by 2020 and 40% energy savings by 2030.

BTO hosted the forum at ASHRAE headquarters in Atlanta, GA. Fifty stakeholders participated, including academics, researchers from national laboratories, manufacturers, and representatives from efficiency advocacy groups. A list of attendees and their affiliations is included in the Appendix.

Objective

The objective of this forum was twofold: 1) Engage participants in a discussion on the key R&D technologies and processes that have the potential to reduce barriers to greater market penetration of high-efficiency HVAC; and 2) Gather a prioritized list of potential R&D activities that can aid BTO in achieving their goals and that industry stakeholders believe will reduce barriers to greater adoption of these highly efficient technologies.

Process and Results

Discussions at the forum included a large group brainstorming session as well as smaller breakout-group sessions. Each attendee participated in three breakout sessions. During the first two sessions, attendees could choose from the following topic areas:

- Residential and light commercial heating/cooling
- Large commercial heating/cooling
- Controls, software, interfaces, usability, and data.

Repeating the above three topic areas during the first two sessions provided attendees with the opportunity to participate in discussions on two of these key topic areas. During the third and final breakout session, attendees could choose from the following new topic areas:

- Distribution and ventilation
- System architecture
- Outside-the-box.

The group brainstorming and breakout sessions together generated a total of 107 unique R&D activities or technology suggestions for BTO to consider (hereafter "initiatives"). At the conclusion of the forum, Navigant posted all of the initiatives on the wall and asked the participants to prioritize the initiatives by voting on the ones that they felt were most valuable and promising for BTO to undertake. Each participant received 5 votes (stickers) to disperse among the different initiatives as they saw fit (regardless of topic area). The following table shows the top initiatives that received 5 or more total votes.[72]

R&D Initiatives Receiving the Highest Votes Overall

Session	Initiative	Votes
Res/Light Com	Develop techniques to raise heat pump performance (all fuels) at low-ambient temperature; consider elimination of defrost (or frost buildup) and backup heat sources	10
Large Commercial	Research different strategies to improve ground-source heat pump (GSHP) performance, siting, installation, modeling, and other aspects to improve their adoption	7
Large Commercial	Demonstrate distributed heating and cooling between buildings (i.e., district)	7
Outside the Box	Investigate new fluids and fluid pairs, including nanofluids, compact heat exchangers, and other material advances to improve absorption heat pumps	6
Distribution & ventilation	Research and develop new air cleaning methods and associated testing standards in order to reduce outdoor air requirements; quantify the associated energy savings benefits	6
Outside the Box	Develop an add-on organic Rankine cycle electrical generator to capture waste heat from an heat pump, chiller, etc.	5
Controls, Software, Data	Conduct laboratory and field testing to help determine the associated energy benefits of FDD systems that meet certain criteria to develop an industry baseline	5

[72] The total number of votes does not equal 5 votes/person multiplied by 50 attendees due to: 1.) Some attendees departed prior to voting; 2.) DOE staff and Navigant facilitators did not vote.

Session	Initiative	Votes
Res/Light Com	Develop improved, publicly available, simple design tools for contractors; consider linking to the AHRI product database	5
Distribution & ventilation	Develop and evaluate techniques for separate sensible and latent control and quantify the energy savings	5

The following tables document each proposed R&D initiative along with the number of votes it received; these tables reflect the raw outputs of the forum. The tables therefore do not perfectly reflect a single category of initiatives, but rather, documentation of the conversations that transpired during the session. The ideas from the forum are divided by the discussion where they arose, including one for the group brainstorming session and one for each of the breakout sessions.

R&D Initiatives from the Group Brainstorm Session

Group Brainstorm – 21 Total Initiatives	
Initiative	**Votes**
Design systems that cannot be misapplied or are more tolerant of misapplication	4
Develop HVAC systems that maximize integration of renewables	3
Develop easy modeling tools to improve building and system design and make it accessible and interpretable by user and consumers alike	2
Provide design guides that focus on systems-level approach to HVAC sizing/design	2
Develop an open-source building automation system to drive innovation	1
Develop optimized components for alternative refrigerant systems	1
Develop residential humidity control systems specifically targeted at low sensible load periods	1
Develop strategies to improve low load performance, especially for commercial cooling systems	1
Conduct materials research to design motors without rare earth metals	0
Develop metrics to inform consumers on soft savings factors including thermostat feedback, over-ventilation of a space, and misapplied systems	0
Develop metrics and test procedures for non-vapor=compression technologies that account for distinct benefits unrecognized in current test procedures	0
Develop smart, variable speed equipment or other strategies to improve low-load performance (focus on high efficiencies at low capacities)	0
Develop a low-cost, open-source continuous commissioning tool that facilitates data availability to show its benefits for others	0
Perform laboratory and field research to better understand the gap between as-designed and as-installed performance	0

Group Brainstorm – 21 Total Initiatives	
Initiative	**Votes**
Conduct research to better understand real world impact of distribution systems on energy consumption	0
Develop an easy, quick, low-cost modeling tool that takes a holistic view of the entire building as a system and publicize it widely	0
Perform research to better understand the ventilation requirements, energy consumption, and humidity impacts of tightly sealed, residential buildings	0
Develop a whole-building residential FDD system that takes a holistic view on sensing and diagnostics	0
Develop strategies to reduce peak demand	0
Evaluate opportunities to reduce size/weight, especially for retrofit applications (e.g., elimination of adapter curbs or need for re-alignment of ducting)	0
Develop techniques to reduce contractor needs/costs for high efficiency and novel equipment	0

R&D Initiatives from the Residential and Light Commercial Breakout Sessions

Residential and Light Commercial – 20 Total Initiatives	
Initiative	**Votes**
Develop techniques to raise heat pump performance (all fuels) at low-ambient temperature; consider elimination of defrost (or frost buildup) & backup heat sources	10
Develop improved, publicly available, simple design tools for contractors; consider linking to the AHRI product database	5
Develop energy analysis tools for the homeowner to conduct a simple economic analysis before purchasing new equipment (focus on existing buildings)	4
Develop a modular or on-board storage for HVAC systems to reduce peak demand; emphasize thermally activated cooling for renewable thermal integration	3
Develop a low-cost expander for waste heat recovery from HVAC systems	3
Perform research to evaluate alternative refrigerants that maintain equivalent or better performance (split system focus)	2
Develop a reliable, self-commissioning unitary HVAC system that is self-aware and provides continuous feedback on system health	1
Develop a single-compressor, integrated building system all-in-one appliance that is built into a single pre-fab energy wall	1
Develop a better interface for monitoring consumption, including a data visualization dashboard	1
Perform economic research on utility programs where high efficiency is often barely above baseline (which incentivizes repairing in lieu of replacing)	1
Characterize the ventilation and humidity requirements in tightly sealed buildings and investigate solutions involving automated exhaust fans	1
Perform education outreach on the value of smart meters, appliances	0

Residential and Light Commercial – 20 Total Initiatives	
Initiative	**Votes**
Develop standardized methods of built-in data acquisition and storage for sizing and equipment selection purposes at end of life	0
Evaluate (paper study and field demonstrations) options for moving heat around buildings (and between buildings) for simultaneous heating and cooling	0
Develop a standardized communication port for add-on sensors, FDD, monitoring, and technician review (e.g., auto industry on-board diagnostics [OBD] standard)	0
Develop membrane-based dehumidification products for residential applications	0
Evaluate holistic approaches to whole-building, complex integrated HVAC systems and determine potential benefits and challenges in retrofit buildings	0
Develop add-on humidity control package, especially for renovations where original structures were not designed for airtight seals	0
Investigate ways to reduce counterfeit refrigerant demand: (1)reduce refrigerant leakage in old equipment, & (2) reduce charge in new equipment	0
Evaluate energy savings from, and pursue development of, nighttime cooling, heating, and storage capabilities, including active & passive ventilation, PCMs, & waste heat recovery	0

R&D Initiatives from the Large Commercial Breakout Sessions

Large Commercial – 20 Total Initiatives	
Initiative	**Votes**
Research strategies to improve ground-source heat pump (GSHP) ground-loop cost & performance; also consider siting, installation, & modeling to reduce costs	7
Demonstrate distributed heating and cooling between buildings (i.e., district)	7
Develop hybrid systems to combine mechanical and natural ventilation techniques	4
Develop cost-effective phase change materials that activate at lower temperatures	2
Research the energy savings, comfort, and IAQ benefits of liquid desiccants and other dehumidification technologies	2
Develop and demonstrate smart equipment with energy recovery or free cooling for simultaneous heating and cooling in large buildings	2
Develop evaporative cooling systems in humid climates and understand the tradeoff between energy and water	1
Develop energy efficient ventilation that enables reduced ventilation rates	1
Research improved terminal distribution systems to adapt to reduced skin loads in buildings	1
Deploy educational lessons from high performance buildings databases (e.g., NREL)	1
Develop low-cost (and legal) sub-metering with intelligent feedback to operators	0

Large Commercial – 20 Total Initiatives	
Initiative	**Votes**
Develop intelligent alarms (not just on/off)	0
Develop an interface between large buildings and smart grid	0
Develop improved modeling tools for district heating and cooling systems	0
Improve modeling tools for variable-speed systems	0
Research improved heat exchanger materials, geometry, surface treatments, etc. including ensuring long-term optimal performance	0
Revisit ventilation rate guidelines	0
Research and demonstrate the energy impacts of maintenance	0
Perform basic R&D on fans and pump efficiency and the entire distribution system	0
Develop a better understand for energy vs. comfort vs. indoor air quality (IAQ) tradeoffs	0

R&D Initiatives from the Controls, Software, Interfaces, Usability, Data Breakout Sessions

Controls, Software, Interfaces, Usability, Data – 16 Total Initiatives	
Initiative	**Votes**
Conduct laboratory and field testing to help determine the associated energy benefits of FDD systems that meet certain criteria to develop an industry baseline	5
Demonstrate different fault detection and diagnostics (FDD) strategies and their benefits to consumer	4
Develop a standardized energy metric for control, FDD, and other systems, including a set of FDD definitions, display, etc.	3
Develop low-cost, reliable, and accurate humidity sensors	3
Develop universal communications protocol and standard communications port for integrated HVAC, water heating, and power systems	3
Develop a low-cost, plug-and-play IAQ monitor that provides usable information besides temp and humidity for high performance buildings	3
Duct system and infiltration diagnostics system for system startup (residential) and ongoing commissioning (commercial)	3
Create a FDD system that translates on-board faults into generic error codes and hierarchal actions to resolve the issue	1
Demonstrate transaction network for rooftop units	1
Develop algorithms and sensors to understand the energy benefits of predictive control	1
Develop a big-data analysis tool to prioritize knowledge with a built-in actionable decision tree	0

Controls, Software, Interfaces, Usability, Data – 16 Total Initiatives	
Initiative	**Votes**
Develop low-cost, in-duct airflow sensors offering high reliability	0
Conduct research to characterize customer tolerance for sensor accuracy, drift, response rate, usability, etc.	0
Develop open-protocol, low-cost commissioning software for building managers	0
Develop a universal communication standard for plug-and-play performance for sensors, FDD, controls, submetering, etc.	0
Develop secure predictive controls based on command/control data	0

R&D Initiatives from the System Architecture Breakout Session

System Architecture – 6 Total Initiatives	
Initiative	**Votes**
Research the pervasiveness of incorrect system commissioning and associated energy impacts	4
Collect data and conduct analysis on the impacts of poor installation, commissioning, and/or operation of HVAC equipment in commercial buildings	3
Develop an app that provides $/hr. energy data for users that reflects local rate structures and sub-metering data to educate occupants	2
Characterize existing residential zoning technologies, including current penetration, and savings potential; identify opportunities; support development of new systems.	1
Research the potential for incorporating large-scale outdoor heat exchangers into building architecture, especially away from the sun (e.g., north side condensers)	1
Develop a standardized efficiency metric for home HVAC systems that is simple and easy for homeowners to understand; emphasize cost and comfort	0

R&D Initiatives from the Distribution and Ventilation Breakout Session

Distribution and Ventilation – 8 Total Initiatives	
Initiative	**Votes**
Research and develop new air cleaning methods and associated testing standards in order to reduce outdoor air requirements; quantify the associated energy savings	6
Develop and evaluate techniques for separate sensible and latent control and quantify the energy savings	5
Develop a standardized building metric to incorporate energy, health, etc.	4
Develop design strategies to reduce the pressure drop in ducts and pipes	1
Perform research and characterize the portion of air leakage in common components, and specify low-leakage components	1

Distribution and Ventilation – 8 Total Initiatives	
Initiative	**Votes**
Develop reliable economizers for dedicated outdoor air systems (DOAS) for zone ventilation	1
Analyze benefits of variable flow over fixed flow for hydronic system and develop best practice tools for existing buildings	0
Develop energy recovery ventilators and other systems with low pressure drop	0

R&D Initiatives from the Outside-the-Box Breakout Session

Outside the Box – 16 Total Initiatives	
Initiative	**Votes**
Investigate new fluids and fluid pairs, including nanofluids, compact heat exchangers, and other material advances to improve absorption heat pumps	6
Develop an add-on organic Rankine cycle electrical generator to capture waste heat from an heat pump, chiller, etc.	5
Develop a small-scale CHP system for electrical power, space heating, space cooling, and water heating	4
Develop a direct-current (DC)-powered HVAC system to utilize DC power from by a solar photovoltaic (PV) system to facilitate microgrid integration	4
Develop and demonstrate seasonal energy storage technologies	3
Develop less expensive magnets for magnetocaloric refrigeration systems	3
Develop a control system of a low-cost sensor network and control scheme where every surface, critical object, and occupant has a sensor (biomimicry considerations)	3
Develop a hybrid adsorption-vapor-compression heat pump storage unit to capture waste via latent heat of evaporation from a water/zeolite mixture	3
Develop electrochemical compression systems	2
Develop creative working fluids for heat recovery, fluid optimization, and other applications.	2
Develop and demonstrate bi-seasonal ice storage for heating and cooling	1
Develop a waste heat recovery engine to capture excess heat from furnaces, particularly RTUs	1
Develop a dehumidification system that can utilize the condensed water vapor on-site, for evaporative condenser make-up water, evaporative cooling, others.	1
Investigate the potential for thermoelectric devices to capture waste heat from a condensing unit	1
Develop fine-grained HVAC control including localized temperature and humidity control	0
Develop efficient dry-cooling techniques to replace large evaporative condensers	0

Next Steps

Navigant, in consultation with BTO, will continue to refine and develop these R&D initiatives though additional research and follow-up interviews with individual stakeholders who were unable to attend the forum. Navigant will combine any duplicate or overlapping initiatives to ensure that all initiatives are unique. We will use a combination of qualitative and quantitative methods in developing final recommendations of the top R&D initiatives DOE to consider. The qualitative prioritization will consider some or all of the following criteria:

- Technical savings potential
- Fit with BTO mission
- Criticality of DOE involvement
- Technical and market risks
- Market Readiness
- Level of required DOE investment
- Stakeholder input (including voting results).

The quantitative prioritization will be based on cost and benefit outputs from BTO's Prioritization Tool.[73] BTO will consider the recommended outputs of these prioritization processes for funding in parallel with other priorities in other building end-use areas. Therefore, no recommended output from this roadmapping process is guaranteed to receive DOE support.

The roadmap will serve as a guide for DOE and its partners in advancing the goal of reducing building energy consumption related to HVAC systems, while maintaining the competitiveness of American industry.

[73] The Prioritization Tool or P-Tool is a Microsoft Excel model that assesses and compares building-related energy-efficient technologies and activities, and projects their potential energy savings and economics. BTO uses the P-Tool to support its programmatic decision-making. The P-Tool draws on data from the Energy Information Administration's (EIA) Annual Energy Outlook (AEO) 2010 to forecast baseline energy consumption in the buildings sector, segregated by geographic location, end use, and fuel type. Tool users input information, including unit energy savings, end use, and applicable market, about efficiency measures of interest. The tool applies these inputs to its baseline energy forecasts to develop estimates of technical energy savings potential, market potential, and the costs of efficiency initiatives, among other outputs. The P-Tool also has the capability of "staging" various efficiency measures, which accounts for the potential interactions among multiple measures.

Appendix: Forum Attendees

Navigant and DOE wish to thank all of the forum participants. The suggestions, insights, and feedback provided during the forum are critically important to identifying and prioritizing HVAC R&D initiatives

The R&D roadmap forum brought together 50 individuals representing a range of organizations across the industry. Table 5-1 lists all the attendees and their affiliations.

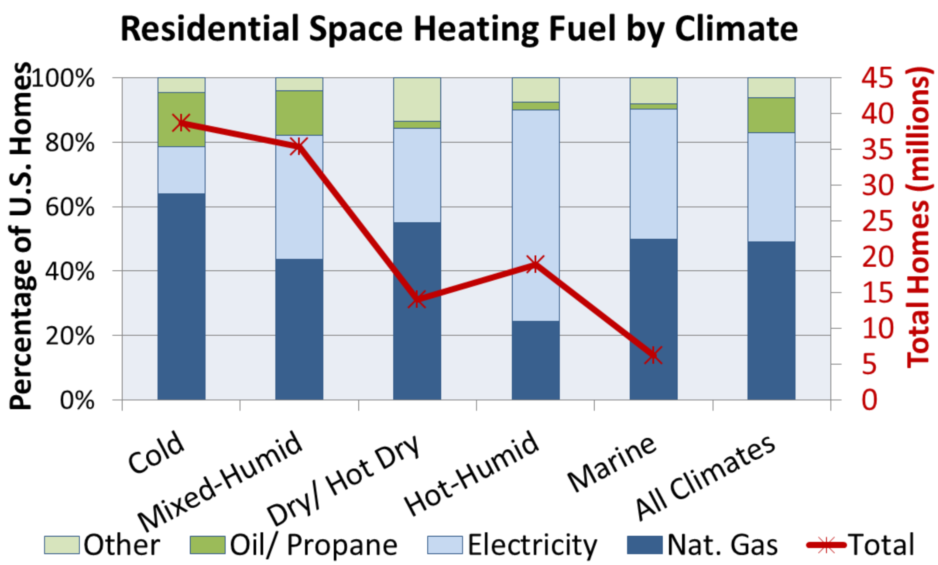
Table 5-1: Stakeholder Forum Attendee List

Attendee Name	Organization
Omar Abdelaziz	U.S. Department of Energy, Building Technologies Office
Van Baxter	Oak Ridge National Lab
Anil Bhargava	I & M Industrials, Inc.
Antonio Bouza	U.S. Department of Energy, Building Technologies Office
Craig Bradshaw	Torad Engineering
Robert Comparin	Emerson Climate Technologies
Dan Dempsey	Carrier
Michael Deru	National Renewable Energy Laboratory
Titu Doctor	CENC Inc.
Ian Doebber	National Renewable Energy Laboratory
Piotr Domanski	National Institute of Standards and Technology
Nicholas Fila	Heery International, Inc.
Douglas Friedman	LabWize, Inc.
Brian Fronk	Georgia Institute of Technology
Brendan Gardes	DLB Associates
Ashok Gidwani	Booz Allen Hamilton / ARPA-e
Chris Gray	Southern Company
Steve Greenberg	Lawrence Berkeley National Laboratory
Chad Griffith	Griffith Engineering
Jill Hootman	Trane
Shaobo Jia	Heatcraft Refrigeration
Brian Johnson	Dais Analytic Corporation
Srinivas Katipamula	Pacific Northwest National Laboratory
Georgi Kazachki	Dayton Phoenix Group, Inc.
Thomas Leck	DuPont
Jason LeRoy	Trane
Dick Lord	Carrier
Chris Muller	Purafil, Inc.
Joe Orosz	Torad Engineering
Hung Pham	Emerson Climate Technologies
Pat Phelan	U.S. Department of Energy, Building Technologies Office
Reinhard Radermacher	University of Maryland
Ari Reeves	CLASP

Attendee Name	Organization
Tom Sayre	Sizemore Group
Ken Schoeneck	Ingersoll Rand
Mick Schwedler	Trane
Harris Sheinman	Heery International, Inc.
Mark Spector	Office of Naval Research
Kristen Taddonio	U.S. Department of Energy, Building Technologies Office
Troy Trant	Rheem Manufacturing Company
Dutch Uselton	Lennox
Parmesh Verma	UTRC
Ed Vineyard	Oak Ridge National Lab
Eric Walthall	Danfoss
Xudong Wang	AHRI
David Wasserman	Southface
Thomas Watson	Daikin Applied
Robert Wilkins	Danfoss
Jing Zheng	Coca-Cola Company
Tony Ziegler	Laboratory & Biosafety System Inc.

6 Appendix B – Supporting Equipment Charts

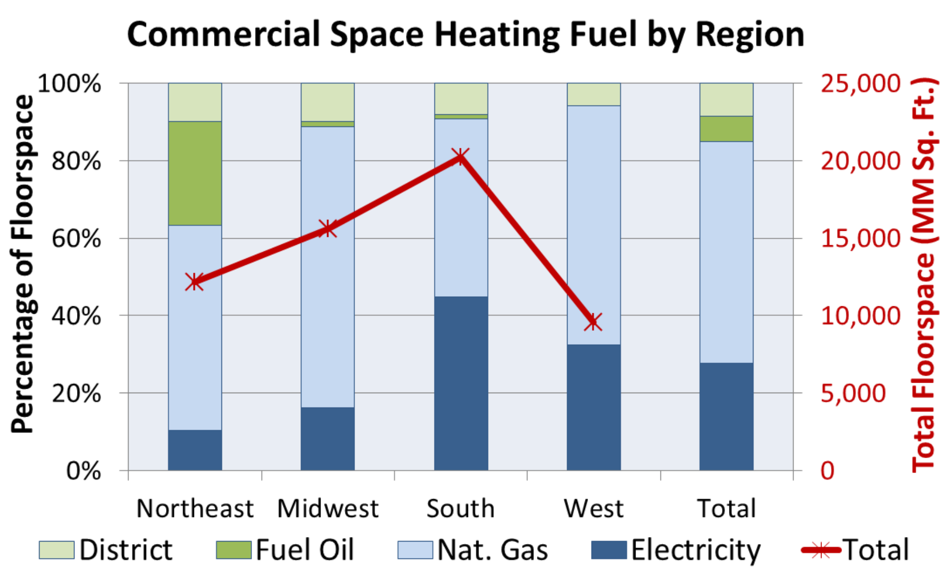
Figure 6-1 shows the fuel split in residences in the U.S. by climate region. The chart, in red, also shows the total number of homes in each region for reference.



Source: EIA Residential Energy Consumption Survey (RECS), 2009, Table HC6.6; more than one equipment type may apply – values do not sum.

Figure 6-1: Residential space heating fuel use in the U.S. by climate

Figure 6-2 shows the fuel split in commercial buildings in the U.S. by region (climate region splits were not available in the CBECS study). The chart, in red, also shows the total floor space in each region for reference.



Source: EIA Commercial Building Energy Consumption Survey (CBECS), 2003, Table B29; more than one equipment type may apply – values do not sum.

Figure 6-2: Commercial space heating fuel use in the U.S. by region

7 Appendix C – Tier 2 Initiatives

The subsections that follow provide detailed descriptions of each Tier 2 initiative. These initiatives were scored during the roadmap development process and are presenting in ranked order below.

7.1 (ID #11) Research and develop new air cleaning methods and associated testing standards in order to reduce outdoor air requirements; quantify the associated energy savings (Direct)

Ventilation requirements, as part of the building code, ensure that sufficient outdoor air is brought into the building to maintain appropriate IAQ for the expected number of occupants of a given space. By providing air cleaning capabilities in a building's HVAC system, the outdoor air load for ventilation can be reduced further. Air cleaners that remove volatile organic compounds (VOCs) and/or scrub CO_2 from the air can enable further reductions, if not complete elimination, of outdoor air ventilation. Current building codes do not typically enable such technologies, except in cases where air cleaning is supplemental to ventilation. In order for this technology to be code-compliant, BTO should support the development of new test methods and standards for efficacy and efficiency of the system. Such standards will ensure that IAQ standards are maintained and that the energy consumption is commensurate with their benefit.

Opportunity: This technology primarily applies to commercial buildings. However, as residential building construction methods become increasingly airtight and outdoor-air ventilation becomes more common, this technology may apply to residential buildings as well. We estimate energy savings similar to other strategies that reduce ventilation such as DCV, which has can reduce energy consumption by 10–30% in buildings having varying occupancy schedules, high HVAC requirements, and/or long hours of operation (Goetzler et al. 2011).

7.2 (ID #12) Develop and demonstrate renewable-integrated district heating, cooling, and power systems for a community, campus, or city (Direct)

Centralized district heating and cooling (DHC) can offer cost and energy savings because the aggregated capacity requirements are usually lower than individual systems, and capacity costs improve when going to larger sizes, thereby offering the opportunity to use higher efficiency technologies or renewable energy sources such as biomass, biogas, solar, etc.

While many cities and campuses in the U.S. have DHC systems, many challenges impede the growth of DHC systems using renewable energy, especially for existing buildings, including high initial cost, complex installation, and logistical challenges of serving multiple buildings and owners. BTO should analyze the lifecycle costs of incorporating renewable energy sources for DHC systems for several building scenarios to assist project developers evaluate their potential cost and energy savings.

Opportunity: The technology is applicable to all heating and cooling for residential and commercial systems in densely populated areas (generally urban, but can be applicable to select densely populated rural areas as well). Some district systems incorporating renewable technologies report a source energy savings of >50% (Goetzler et al. 2012). We estimate a source energy savings of 20% or more may be achievable depending on the baseline system.

7.3 (ID #13) Continue development of reliable and cost-effective FDD strategies for a variety of HVAC systems (Direct/Enabling)

FDD systems alert building operators of various problems associated with HVAC equipment and systems, and in recent years have debuted for light-commercial RTUs and residential split-systems. These FDD systems detect equipment malfunction through a variety of means including a suite of pressure and temperature sensors located throughout the HVAC system, non-invasive sensors that rely on electrical or acoustic patterns during equipment operation, and other techniques. BTO has supported the development of FDD algorithms and commissioning tools for residential and light-commercial HVAC equipment, but additional research can improve upon current methods by incorporating operational learning, more effective communication strategies, incorporating variable-speed, hybrid HPs, and other equipment classes, and other activities. BTO should continue to support the development of embedded or add-on software and controls that enable the reliable continuous monitoring and commissioning of unitary HVAC systems.

Opportunity: The technology is applicable to all residential and commercial buildings
We estimate 15% savings if you assume most systems run with a fault (Goetzler et al. 2012).

7.4 (ID #14) Continue the development and demonstration a next-generation window A/C with high-EER performance and advanced features to reduce losses (Direct)

Window or room A/Cs and HPs typically have lower efficiency than centralized systems and suffer from poor thermal distribution, outside air infiltration, and other issues. BTO has supported research into understanding the performance of window A/Cs and designating best practices at NREL, and the development of a 13 EER window A/C with ORNL and a CRADA partner (GE). BTO should continue to support the development and demonstration of high efficiency window A/Cs by incorporating components which raise standard efficiency metrics (e.g., high efficiency or variable speed compressors), and features which reduce other associated losses (e.g., occupancy sensors, improved thermal distribution techniques). With federal standards rising in June 2014, demonstrating high efficiency units will support the pipeline for higher ENERGY STAR specifications and utility rebates.

Opportunity: The technology is applicable to non-centralized heating and cooling systems for residential systems. Savings depends on the baseline system and may reach 15% or greater (assumes 13 EER over 11 EER).

7.5 (ID #15) Develop an open-source building automation system to drive innovation (Enabling)

Depending on the size and complexity of the building, building controls can range from simple thermostat commands for a single RTU to a centralized building automation system that controls the HVAC, lighting, security, fire suppression, and other systems. Building energy management and automation systems offer the opportunity to analyze large amounts of monitoring data to derive more efficient and cost-effective scheduling algorithms for HVAC and other equipment. Nevertheless, building owners do not implement these systems due to the large upfront cost and uncertain payback periods, especially for smaller commercial and residential buildings. BTO has supported the development and demonstration of energy saving algorithms for building automation systems through the OpenEIS program and other activities. BTO should continue to support strategies that provide independent demonstration for energy, cost, and performance benefits from building automation systems and facilitate their use in smaller buildings through open-source algorithms and networking platforms.

Opportunity: The technology is applicable to all residential and light commercial HVAC systems with savings of approximately 15% (Hagerman 2014).

7.6 (ID #16) Develop a standardized building metric to incorporate energy, health, etc. (Enabling)

Because most people spend the majority of their time within buildings, maintaining high indoor environmental quality (IEQ) is crucial to the health and function of the building occupants, whether it be at home, work, entertainment, or other daily activities. IEQ encompasses not only temperature and humidity control, but also proper ventilation, noise, safety, happiness, and other factors that contribute to high occupant productivity and reduced absenteeism by maintaining occupant well-being. To help balance these factors, ASHRAE and other industry organizations continuously update ventilation and IAQ standards (e.g., Standards 62.1 and 62.2) as well as IEQ standards for high performance buildings (e.g., Standard 189.1). Unlike energy or water efficiency, measuring IEQ in an effective and economic way during building operation is difficult because of the multitude of factors that contribute to proper IEQ. Researchers at National Institute of Standards and Technology (NIST) and other organizations are developing ways to measure and quantify building IEQ, which can ultimately lead to standardized IEQ metrics and facilitate the real-time optimization between IEQ and energy efficiency in buildings. BTO should support development of standardized IEQ measuring techniques and rating systems and perform research into strategies that maintain high IEQ at lower energy consumption.

Opportunity: This initiative is applicable to all residential and commercial buildings.

7.7 (ID #17) Investigate the prevalence of simultaneous heating and cooling in buildings and evaluate energy recovery and improved thermal distribution methods (Direct)

Many large commercial buildings, such as offices, experience different thermal loads throughout the building, even on the same floor. For example, the perimeter of the building may differ significantly from more internal areas such that one area requires heating, while the other requires cooling to maintain comfortable conditions. In these and other cases where simultaneous space heating and cooling is required, HVAC system designers have utilized a variety of technologies to recover thermal energy in one zone to satisfy another, including run-around pipes, heat pipes, energy recovery wheels, HPs, and heat recovery variable refrigerant flow systems. While several of these technologies have seen wider application for pre-conditioning ventilation air, their usage to provide more efficient thermal distribution within the building has been limited due to custom design and complex installation, especially for retrofits. BTO should conduct an analysis to understand the magnitude of the simultaneous heating and cooling problem in commercial buildings and support the development and demonstration of more efficiency thermal distribution strategies.

Opportunity: The technology is applicable to commercial buildings, particularly large buildings. The energy savings may reach 20% based on partial savings from ductless multi-split systems (Goetzler et al. 2012).

7.8 (ID #18) Duct system and infiltration diagnostics system for system startup (residential) and ongoing commissioning (commercial) (Direct/Enabling)

Duct leakage and outside-air infiltration are two of the most common causes of poor building performance. Both increase energy consumption by delivering air to an unwanted location within the building i.e., either into (infiltration) or outside (duct leakage) the conditioned space. To help identify the presence of duct leakage and excess infiltration, several diagnostic tests are available and often required for some building codes, including the blower-door test, duct pressurization test, Delta Q test, tracer gas test, and infrared imaging. Once diagnosing the problem, contractors will employ several treatment options including: aerosol, mastic, or caulk sealants, creating an air barrier, and physical repair. While these practices help to reduce the increased energy consumption in the near term, the problems of duct leakage and infiltration can reoccur over time as repairs degrade and new problems occur. Several researcher teams (e.g., Taitem Engineering Inc. / Cornell University and Argonne National Laboratory/Illinois Institute of Technology) are currently investigating the potential for next-generation diagnostic systems using acoustical analysis, continuous monitoring, and other methods. BTO should support research into improved diagnostic systems and sensors that allow for alternative and/or continuous measurement of duct leakage and building infiltration.

Opportunity: The technology is applicable to all residential and commercial HVAC systems. We estimate savings of 10–15% and greater based on Quality Installation savings (Goetzler et al. 2012).

7.9 (ID #19) Develop a small-scale, low-cost, CHP system for electrical power, space heating, space cooling, and water heating (Direct)

Thermal and electrical energy generation systems lose some of their energy transportation to the home or rejected as waste heat. For large commercial and industrial applications, on-site combined cooling, heat, and power or tri-generation systems capture the waste heat of a gas-fired electrical generator (e.g., engine or turbine) to produce hot water for space and water heating, and to drive an absorption chiller for space cooling. For smaller applications, various products including electric or gas-driven IHPs (space heating, space cooling, and water heating) and micro-CHP engines or fuel cells (electricity, space heating, water heating), contain only some of these features. A packaged, all-in-one building energy system could potentially utilize more of the primary energy contained within fossil fuels and reduce utility costs for smaller residential and light commercial buildings. BTO has supported the development of a residential, fuel-fired HP for space conditioning, water heating, and power generation through a CRADA partnership with ORNL and Southwest Gas. BTO should continue to support the development small-scale, CHP systems utilizing engine, fuel cell, and other electrical generating systems tied with vapor-compression, thermally activated, or other alternative space cooling systems.

Opportunity: The technology is applicable to all heating and cooling systems for residential and light-commercial applications. Energy savings of 20% or greater may be achievable, especially in heating-dominated climates based on engine-driven HP savings (Goetzler et al. 2012).

7.10 (ID #20) Develop hybrid systems to combine mechanical and natural ventilation techniques aka mixed-mode conditioning or integrated window ventilation (Direct)

Mixed mode conditioning is a hybrid technique for ventilating commercial buildings that uses mechanical systems in conjunction with operable windows (automated or manual) to provide energy –efficient ventilation to the building. Each implementation has historically been a custom-designed system, which keeps cost high. Not only do such approaches provide energy savings, they also enable the use of smaller size equipment for capital-cost savings, as well as greater occupant comfort, reduced wear and tear on mechanical systems, and longer equipment life. Most large commercial buildings in the U.S. are built with inoperable windows to prevent occupants from opening windows to meet localized comfort needs and inadvertently putting greater load on the HVAC system. BTO should support the development and demonstration of standardized mixed-mode conditioning systems.

Opportunity: This technology applies to all commercial buildings with mechanical ventilation systems. In the future it may also apply to increasingly common tightly sealed residential buildings as well that require mechanical ventilation. Energy savings estimated at 15%–80% depending on climate, building type, and cooling loads (Goetzler et al. 2011).

7.11 (ID #21) Characterize existing residential zoning technologies, including current penetration, and technical savings potential; identify new low-cost, non-invasive technologies for retrofit systems (Direct)

System designers have developed strategies to introduce zoning for residential centralized systems where multiple thermostats control a damper within a dedicated supply duct such that each zone receives the correct amount of airflow. These systems aim to optimize comfort in occupied zones while saving energy in others. Such systems have been shown to improve comfort, but have had mixed experiences from an energy standpoint, especially when using constant-speed supply fans. Manufacturers and service providers have developed several new technologies in recent years that could improve residential zoning systems, including: variable-speed blowers, predictive thermostats, Wi-Fi controls, automated register dampers, and other components. BTO should analyze the potential energy savings and comfort benefits from advanced residential zoning systems through modeling simulations and field demonstrations, and if promising, develop techniques to improve the design, installation, and control of zoned HVAC systems, especially for existing buildings.

Opportunity: The technology is applicable to all residential central, ducted HVAC systems. Savings estimates range widely, we estimate 0–20% savings based on Zocor et al. (2012).

7.12 (ID #22) Develop and demonstrate next generation of chiller technologies for large commercial buildings (Direct)

Large multifamily residential and commercial buildings commonly use large, centralized vapor-compression HPs (i.e., chillers) to generate chilled water for space cooling. In recent years, manufacturers have significantly raised chiller efficiency at full- and part-load conditions by incorporating variable frequency drives (VFDs), magnetic or ceramic bearings, heat recovery, high-efficiency motors, improved compressor designs, advanced controls, optimized schedulers, and other technologies. The planned phase-out of the current generation of high-GWP refrigerants requires further advances to maintain performance and efficiency of future chillers. BTO should support the development and demonstration of next generation of chiller equipment using low GWP refrigerants, non-vapor-compression cycles, or other technologies.

Opportunity: The technology is applicable to large multifamily residential and commercial systems. Limited savings potential, but prevents potential efficiency decreases due to alternative refrigerants.

7.13 (ID #23) Develop solar HPs using thermally activated heating and cooling technologies (Direct)

Solar thermal HPs collect solar radiation to generate hot water that drives thermally activated cooling and/or heating systems such as absorption or adsorption heat pumps and liquid or solid desiccant A/Cs. The solar collectors, either flat plate or evacuated tube, are sized to meet the temperature and thermal output requirements of the particular heating and/or cooling system, and are typically accompanied by a back-up fuel-fired water heating system and hot water storage tank. By capturing the low-cost, renewable thermal energy, solar thermal HPs have lower source energy consumption even when coupled with a low-efficiency cooling cycle. While the technology is commercially available in Europe and other markets, the high cost of the technology relative to natural gas poses a barrier to larger market adoption in the U.S. DOE has supported the development of solar thermal collection and storage, and thermally activated HPs through numerous initiatives. DOE should support the further development of low-cost solar thermal collectors as well as thermally activated HPs by investigating alternative architectures, utilizing advanced materials and working fluids, and other strategies.

Opportunity: The technology is applicable to residential and commercial heating and cooling systems with a project savings potential of 30% (Goetzler et al. 2011).

7.14 (ID #24) Develop energy efficient ventilation and space conditioning techniques that reduce HVAC loads through the use of microclimates, personal comfort devices, or other small-scale comfort devices to control specific parts of a room. (Direct)

Most residential and commercial buildings deliver space conditioning and ventilation to occupants using large, centralized duct systems. While blowing conditioned air into building spaces through the floor, wall, or ceiling is a relatively straightforward distribution mechanism, thermal and fan energy may be wasted due to thermal stratification and heating/cooling the entire room to make sure occupants receive fresh and conditioned air. Researchers have investigated alternative strategies to more efficiently provide comfort and ventilation to occupants through smaller, more directed conditioning systems known as personal comfort or microclimate devices. These systems come in various configurations but typically are either worn on the person or integrated into or around furniture (e.g., office workspace). DOE has supported such research through Advanced Research Projects Agency-Energy (ARPA-e) Delivering Efficient Local Thermal Amenities (DELTA), LBNL, and other organizations, and should continue to investigate these alternative space comfort and ventilation approaches through simulation modeling, prototype development, and field demonstrations.

Opportunity: The technology is applicable to all residential and commercial HVAC systems and has a potential energy savings of 30% (Zhang 2012).

7.15 (ID #25) Continue the development and demonstration of high-performance packaged HVAC systems (Direct)

Because packaged RTUs serve such a large portion of the U.S. light commercial market and commonly operate at off-design conditions, advancements in full- and part-load space cooling efficiency can drive significant energy and peak demand savings. Incorporating techniques such as variable speed drives, high-efficiency motors and compressors, multiple modulating compressors, microchannel heat exchangers, low pressure airflow design, evaporative pre-cooling, etc. can collectively raise the IEER of packaged rooftop A/Cs well above baseline standards for 10–20 ton units. BTO has supported advanced RTUs through simulation performance mapping of various technologies at ORNL, performance testing to the Better Buildings Alliance's High Performance Rooftop Unit Specification, and other initiatives to develop equipment with 18 IEER and greater. Building on these efforts, BTO should continue to develop strategies, components, and tools to enable high IEER RTU design, conduct field testing with applicable models to objectively demonstrate their performance, and develop lifecycle energy and economics tools to quantify the benefits in various climates.

Opportunity: The technology is applicable to all light commercial packaged A/C and HPs. Savings is estimated at 25–50% depending on the climate and baseline (assumes IEER baseline is 11).

7.16 (ID #26) Conduct nan-fluids research for advanced distribution fluids, refrigerant pairs, surfactants (Direct)

Developments in materials science have created nanoscale materials that could have a significant impact for HVAC systems through advanced coatings on heat exchangers and improved primary or secondary working fluids. For heat exchangers, such materials could improve evaporation and condensation through enhanced heat transfer or inhibit the formation of ice or fouling. For working fluids, the nanoparticles could raise the thermal conductivity of the fluid, facilitating greater transfer of heat at a lower pumping requirement. BTO has supported research at Argonne National Laboratory and other institutions to better understand the potential for various types and sizes of nanofluids. BTO should continue to support research into understanding the heat transfer properties of nanofluids and then investigating their potential for use with materials and working fluids common to the HVAC industry.

Opportunity: The technology is applicable to fan and pump energy for all HVAC systems. Energy savings is potentially very high. Energy savings estimates for full HVAC systems are unavailable, but we estimate 27% savings based Kulkarni et al. (2007).

7.17 (ID #27) Develop energy analysis tools for the homeowner to conduct a simple economic analysis before purchasing new equipment (focus on existing buildings) - homeowner focus (Enabling)

As more homeowners consider high efficiency HVAC equipment, customers are most interested in the energy and cost savings that could be achieved by these advanced features. Several analysis tools and economic calculators are available, but are often overly complicated, imprecise for their home, or potentially biased in the minds of the consumer. A simplified tool that considers the size, age, and location of the home, recent utility bills, thermostat set-points, and other easy-to-obtain information could assist the homeowner with their decision over high efficiency equipment, especially if provided or certified by an independent source. BTO has developed some of these features through simulation software (e.g., BEopt), PNNL's Rooftop Unit Comparison Calendar, as well as Federal Energy Management Program (FEMP) and ENERGY STAR product savings calculators. BTO should support the development of a simplified and streamlined economic analysis tool to assist with purchasing decisions for residential HVAC systems. In lieu of designing the entire tool, BTO could also develop a specification or application programming interface (API) outlining the assumptions, algorithms, features, etc. that would provide a standardized methodology for third-parties to then develop the user interface or incorporate in their offerings to customers.

Opportunity: The technology is applicable to all residential HVAC systems.

7.18 (ID #28) Compile the lessons learned from NREL's high performance buildings database and develop tools, guides to educate the industry (Enabling)

Developed by BTO and NREL in the mid-2000s, the High Performance Buildings Database serves as a central repository of detailed information on high-performance residential and commercial buildings. The database summarizes key building details, design features, actual energy and water usage, contact information, and other aspects to help prospective building owners or project designers consider more energy and environmentally conscious buildings. With substantial information about each building and its energy consumption, the database can provide valuable lessons to the building industry about effective design features. BTO should analyze the database to understand the most effective and commonly used practices and develop a best-practice guide for the industry. If possible, BTO could also follow up with each of the buildings to understand how their satisfaction, comfort, and energy consumption has changed since submitting the initial profile.

Opportunity: The technology is applicable to all residential and commercial HVAC systems.

7.19 (ID #29) Develop universal communications protocol for integrated HVAC, water heating, and power systems, allows plug-and-play compatibility (Enabling)

Manufacturers and vendors of a variety of residential and commercial appliances are incorporating communication and control systems to interact with the smart grid as distributed energy resource. Whether through a central energy management system or individual connection, these connected devices can change their operating schedules or reduce their consumption during peak demand events or high time-of-use (ToU) rate periods. Accounting for a large percentage of building energy usage, HVAC systems are a key piece for demand response and other grid-interactive strategies. For the greatest benefit, each of these appliances and systems should coordinate their response to the grid-interactive signals, but currently experience integration issues related to various communication protocols and metrics that characterize the capabilities of each appliance or system. BTO and other industry groups are working to develop communication and measurement protocols that can facilitate easy, plug-and-play integration of the various grid-enabled appliances. BTO should continue to develop standardized protocols for grid-enabled appliances and analyze their potential energy and cost savings through field demonstrations.

Opportunity: The technology is applicable to all residential and commercial buildings.

7.20 (ID #30) Develop a modular or on-board storage mechanism for HVAC systems to reduce peak demand, including RTU energy storage and thermally activated cooling for renewable thermal integration (Direct)

Packaged RTUs are the most common commercial space cooling equipment in the U.S. During the summer months, these RTUs collectively represent a large contribution to the increased demand curve utilities experience. Similar to ice or chilled water systems available for large, built-up, cooling systems, integrated-RTU thermal energy storage offers the opportunity for RTUs to reduce peak demand and utilize operational favorable ToU electricity rates by shifting the production of cooling to off-peak hours. Additionally, such systems would experience minimal efficiency loss as the slight increase in consumption of the storage system during the day is offset by utilizing the lower ambient temperatures and reduced cycling losses during nighttime cooling production.

The few existing product offerings are expensive and complex. Additionally, the technology has little penetration in the residential market, where packaged systems and demand or ToU rates are less common. BTO should support research into developing lower cost thermal energy storage systems, which easily integrate with common HVAC equipment types in the residential and light commercial market, especially for existing buildings and systems.

Opportunity: The technology is applicable to all residential and light commercial HVAC systems. Energy savings is minimal, at 0–5% of overall usage and will vary with nighttime ambient temps, but peak demand savings may reach 12–25% (Goetzler et al. 2011).

7.21 (ID #31) Develop standardized fault definitions, thresholds, and communication protocols to improve the operability and user-interaction with FDD systems (Enabling)

Because HVAC systems consist of multiple pieces of equipment that are not necessarily from the same manufacturer or installed at the same time, FDD systems can only operate effectively if each component shares data on operating status, efficiency, and other information in a standardized manner. BTO should support efforts to standardize fault definitions, thresholds, and communication protocols to increase the interoperability of FDD systems. BTO can use the results from laboratory and field demonstrations of various FDD strategies and thresholds as the underlying data to support industry-wide discussions on common FDD definitions, alert messages, and other aspects to improve communication with other HVAC or BAS systems and the building operator.

Opportunity: The technology is applicable to all residential and commercial buildings.

7.22 (ID #32) Develop a low-cost, IAQ monitor that provides usable information besides temperature and humidity for high performance buildings (Enabling)

ASHRAE and other organizations have specified ventilation rates for different building types to ensure the HVAC system is properly sized to supply and condition sufficient outside air. Matching ventilation rates to the actual needs of the building (i.e., demand-controlled ventilation, DCV) can ensure safe and healthy indoor environment while also minimizing energy usage. DCV systems utilize CO_2 or other sensors to modulate the supply of outdoor air based on building or room occupancy. While CO_2 levels are a good proxy for the human-sourced contaminants, particulates from cooking equipment, dust, off-gassing from consumer products, and other contaminants remain unmonitored from conventional thermostats and IAQ sensors. By not monitoring these additional IAQ contaminants, the building's ventilation rate may be misaligned with the required amount. Researchers at NIST, the EU's IAQSense program, and various vendors are developing low-cost, stationary IAQ monitors that measure a wide array of contaminants to replace the expensive portable systems today. BTO should support the development of these advanced IAQ monitors, and analyze control schemes and techniques to incorporate the readings with residential and commercial ventilation system to ensure proper ventilation rates without excess thermal and fan consumption.

Opportunity: The technology is applicable to all residential and commercial buildings.

7.23 (ID #33) Research strategies to improve ground-source heat pump (GHP) ground-loop cost and performance; also consider siting, installation, and modeling to reduce costs (Direct/Enabling)

Geothermal heat pumps (GHP), also known as ground-source heat pumps (GHPs) achieve high efficiency by utilizing the relatively stable temperatures below the Earth's surface as a thermal source and sink. Because the ground maintains a moderate temperature year-round compared to ambient air, the HP can transfer heat over a smaller temperature difference, raising efficiency in both the heating and cooling seasons. Despite this inherent efficiency advantage, GHPs have been limited by their substantial upfront cost premium over other technologies due to custom design and installation complexity for the site-specific ground-loop. DOE should support the development of advanced heat exchanger techniques, integrated design and simulation tools, long-term monitoring of installations, lifecycle energy and cost evaluation tool, and best practice guides to reduce the cost and uncertainty of GHP systems. Further details on specific initiatives related to GHPs are contained in BTO GHP R&D Roadmap.

Opportunity: The technology is applicable to all heating and cooling applications for residential and commercial buildings. This technology is also applicable to all climate regions and building types, although favored for new construction where landscaping issues are less of a concern, and suburban/rural areas where the available space is more prevalent. Source energy savings can reach 25% or more (Goetzler et al. 2012).

7.24 (ID #34) Conduct laboratory and field testing to help determine the associated energy and non-energy benefits of FDD systems and develop an industry baseline for measuring performance (Enabling)

Equipment manufacturers, energy management system (EMS) vendors, and service providers have recently expanded FDD-enabled product offerings, particularly for light-commercial RTUs and residential split-systems. Uncertainty remains on the best configuration of sensors and software for FDD systems, and accurate estimates energy and operational savings. BTO and other organizations have supported the development and market entry of various sensors, diagnostic strategies, and communications systems for residential, light-commercial, and large-commercial HVAC systems. To further support the emergence of reliable and energy-saving FDD systems, BTO should conduct independent, laboratory and field testing of various FDD strategies to verify the energy savings and other benefits from FDD systems over time. This testing will help identify minimum requirements for FDD systems to meet energy saving goals, and can help develop standardized test protocols to demonstrate effective FDD strategies.

Opportunity: The technology is applicable to all residential and commercial buildings.

7.25 (ID #35) Develop alternative non-solid-state, non-thermally activated HPs with suitable efficiency, cost, and performance compared to next generation HVAC equipment (Direct)

While vapor-compression systems have been the dominant space cooling technology for close to 100 years, the conventional refrigerants used in vapor-compression equipment contribute to global climate change when released to the atmosphere. The anticipated commitment to reduce Hydrofluorocarbon (HFC) consumption has stimulated interest in alternative refrigerants with low-GWP, but many of these alternative refrigerants potentially trade a GWP advantage for disadvantages related to toxicity, flammability, lower efficiency, and/or increased equipment cost. Various non-vapor-compression cooling cycles exist that use electrical energy to alter a working material's phase or other properties to pump heat, including: thermoelastic, membrane HPs, evaporative cooling, and others. These alternative cycles offer the potential for significant energy savings over current and future vapor-compression systems

Recent laboratory experimentation and theoretical analyses into these non-solid-state, non-thermally activated cycles suggest the potential for high efficiency in space-conditioning applications, but each requires further demonstration before consideration as a viable alternative to vapor-compression technology. BTO has supported several of these technologies at various stages in their design cycle, from early stage materials research, to laboratory experimentation, and even prototype design for limited applications. BTO should continue to support prototype development and demonstration for the most promising applications to not only benchmark performance against conventional systems, but to also find areas for future improvement.

Opportunity: Technically applicable to all cooling (and potentially heating) applications for residential and commercial buildings in all climate regions. Depending on the baseline system, source energy savings of 25% and greater (Goetzler et al. 2014)

7.26 (ID #36) Develop a waste heat recovery engine, for power, to capture excess heat from condensing units or from furnaces including thermoelectrics, organic Rankine cycle and other generating processes/technologies (Direct)

Both fuel-fired heating and vapor-compression cooling equipment generate and then reject excess heat, typically to outside air. While products exist to capture this waste energy to preheat service water (e.g., a desuperheater), the waste heat often exceeds what can be used on-site in a given time period or economically stored. Certain industrial and transportation applications have utilized organic-Rankine cycles, thermoelectric generators, and other recovery systems to generate electrical energy from the wasted heat energy. Because this generated power can offset grid-purchased electricity throughout the building or be sent to the utility's grid in a net-metering configuration, heat-to-electricity recovery systems offer greater flexibility.

HVAC systems generate large amounts of waste heat; however, current heat-recovery technologies require significantly larger temperature differences than those produced by space conditioning equipment. Even in optimal situations, the recovery efficiency of current heat-to-electricity systems is generally low, especially compared to thermal recovery systems. If current research efforts in the industrial and transportation sectors improve the efficiency, cost, and performance of low temperature heat recovery systems, BTO should investigate their potential for HVAC systems through analytical and laboratory research.

Opportunity: The technology is applicable to all fuel-fired heating and vapor-compression cooling for residential and commercial systems. Energy savings is low due to low temperature differences – 10–20% max, but most likely 5% (Kumar et al. 2013).

7.27 (ID #37) Develop reliable economizers for packaged air handlers and dedicated outdoor air systems (Direct)

In light commercial rooftop A/Cs, economizers modulate the amount of outside air that enters the building for both ventilation control and space cooling when conditions permit. While RTUs using this feature can achieve significant energy savings, field studies have shown that economizer sensors, controls, linkages, etc. commonly malfunction and fail, reducing the energy savings benefit, or even increasing consumption due to excess ventilation. To address this issue, California Title 24 building codes and other standards have developed warranty, reliability, FDD, and other requirements to reduce the likelihood of economizer malfunction. BTO should support efforts to improve the reliability and effectiveness of air-side economizers for packaged HVAC systems by developing more robust economizer components, incorporating guidelines into high performance equipment specifications, and performing field demonstrations to demonstrate the improvements.

Opportunity: The technology is applicable to light commercial packaged HVAC equipment with savings of 10% or greater due to fixing the malfunctioning units (Goetzler et al. 2011).

7.28 (ID #38) Develop a universal communication port to facilitate technician interaction on-board monitoring and FDD systems for unitary HVAC systems (Enabling)

For unitary HVAC equipment, on-board diagnostic systems can communicate increased energy consumption, improper cycling, and other faults to building owners or contractors, signaling the need for equipment maintenance. Because building operators commonly have different equipment and components from several manufacturers, a universal communications port on unitary equipment could allow technicians to review the faults of all equipment, regardless of make. Functioning much like the diagnostics port of automobiles, the technician would connect an electronic device to the unit’s communications port and have a full readout of the system status, fault log, and other information. BTO should support the development of standardized communication port for FDD of unitary HVAC equipment by identifying the required features, capabilities, and components, working with industry groups to develop standards, developing prototype systems, and performing field demonstrations.

Opportunity: The technology is applicable to all residential and commercial buildings.

7.29 (ID #39) Provide easy-to-use design guides that focus on systems-level approach to HVAC sizing/design (Enabling)

High performance buildings require careful planning to coordinate the various subsystems that contribute to an efficient and effective indoor environment. Rather than isolating different building loads and subsystems during the design phase, building designers can anticipate future operational problems and discover efficiencies by incorporating a systems- or building-level approach to HVAC sizing and design. For example, considering the equipment size and location of central A/C, dehumidifiers, ERVs, kitchen and bathroom exhaust systems, HPWHs, and other equipment can avoid excessive envelope penetrations, multiple duct runs, oversized equipment, poor IAQ, and other issues. DOE should support the development of easy-to-use design guides that focus on a systems-level approach for residential and commercial HVAC systems by leveraging building science research as part of Building America and other programs, and coordinating with various industry groups.

Opportunity: The technology is applicable to all residential and commercial HVAC systems.

7.30 (ID #40) Develop improved aerosol duct sealing materials, application systems, and methods (Direct)

Aerosol duct sealing reduces the common issue of air leakage in residential and light-commercial ductwork by introducing an aerosol spray into the ducts, which then builds up on cracks and holes as it tries to escape through leaks. Originally developed at LBNL, aerosol duct sealing is now available nationwide and has reduced leakage in over 100,000 homes. Nevertheless, the process still takes considerable time and potential benefits are somewhat uncertain until after application. Developing advanced diagnostic techniques, more expedient application times, and strategies to remediate larger sized holes would improve this technology's value proposition to consumers and subsequent national energy savings. BTO should continue to support this technology by developing improved sealing materials, application systems, diagnostic methods, and other strategies that can help reduce the time and cost of application while improving the capabilities of the aerosol duct sealing process for larger and more complex applications.

Opportunity: The technology is applicable to residential and commercial buildings with an estimated 10% energy savings potential (Goetzler et al. 2011).

7.31 (ID #41) Develop a low-cost, open-source continuous commissioning tool that facilitates data availability to show its benefits for building managers and others (Enabling)

During the course of normal operations, building systems commonly lose efficiency and performance as HVAC equipment requires maintenance, control schedules and set-points are adjusted and operating conditions change. While certain issues are readily identifiable, many causes of inefficiency are more subtle and can linger for long periods of time before identification. Continuous or ongoing commissioning software benchmarks the performance of HVAC and other building systems to identify potential faults, and direct maintenance to restore efficiency. While multiple vendors offer ongoing commissioning services for larger buildings, light commercial and residential buildings could also benefit from the technology as part of an automated FDD system. BTO should support the development of an ongoing commissioning dashboard that utilizes the information gathered by smart meters and the FDD systems of HVAC equipment to benchmark energy use and runtime against predictive consumption based on weather, past history, and other information sources.

Opportunity: The technology is applicable to all residential and light commercial HVAC systems and can help achieve 10–15% savings (Goetzler et al. 2011).

7.32 (ID #42) Develop metrics and test procedures for non-vapor=compression technologies that account for distinct benefits unrecognized in current test procedures for conventional equipment (Enabling)

Several non-vapor-compression technologies show promise as viable alternatives to vapor-compression-based systems. While these systems can provide energy savings, they also offer many non-energy benefits, some of which are as important as or more important than HVAC energy savings alone. When supporting the development of non-vapor-compression technologies, BTO should develop test procedures and rating schemes to better quantify the value of non-energy benefits during laboratory and field testing and compare the performance for conventional and non-vapor-compression systems. This initiative may increase in attractiveness over time assuming non-vapor-compression HVAC technologies come closer to commercialization.

Opportunity: The technology is applicable to all residential and commercial HVAC systems.

7.33 (ID #43) Develop, test, and demonstrate optimized predictive scheduling and control systems to determine the associated energy and performance benefits (Direct)

Control strategies for HVAC systems typically combine reactive and scheduled approaches to information from sensors or building operators. Equipment manufacturers, software and control vendors, and other service providers have developed strategies to improve the performance and efficiency of HVAC systems by using historical data, weather forecasts, utility pricing, and other information sources to optimize equipment scheduling. BTO should conduct an analysis of these various predictive control techniques to understand the associated energy, cost, and performance benefits through simulation analysis, documenting case studies, and other initiatives to provide independent verification for residential and commercial buildings building operators.

Opportunity: The technology is applicable to residential and commercial buildings with savings of approximately 10% (Goetzler et al. 2012).

7.34 (ID #44) Develop simple and straightforward modeling tools focused on contractor usability to improve building and system design (Enabling)

Contractors utilize several tools to properly size and design residential HVAC systems, such as ACCA Manual J or S, and to develop energy and cost estimates for baseline and high efficiency equipment. While recommended as part of best practices, these tools are often difficult to use at the customer site due to their length and complexity. This encourages contractors to make approximations to quickly provide recommendations to customers. Additionally, without a full energy and economic analysis for their home, the customer is hesitant to purchase higher efficiency equipment. BTO should support the development of an independent, simplified, and streamlined sizing tool and calculator for energy and cost analyses that the contractor can quickly complete on-site and communicate to the homeowner. In lieu of designing the entire tool, BTO could also develop a specification or API outlining the assumptions, algorithms, features, etc. that would provide a standardized methodology for third-parties to then develop the user interface or incorporate in their offerings to customers.

Opportunity: The technology is applicable to all residential HVAC systems. Energy savings is 10–15% compared to Quality Installation (Goetzler et al. 2012).

7.35 (ID #45) Research the potential benefit of thermoelectrically enhanced subcoolers, and if promising develop prototype systems (Direct)

By reducing the refrigerant enthalpy after the primary condenser stage, subcoolers increase the cooling capacity of vapor-compression systems without additional input from the primary compressor. Because thermoelectric devices have shown to produce low temperature lifts at relatively high efficiency, a subcooler using one or more thermoelectric coolers could provide additional capacity with only a minor increase in energy consumption (or potentially no consumption if using thermoelectric energy harvesting), and improve system efficiency. While research suggests this concept may be possible, challenges remain to create an efficient, reliable and cost-effective subcooler with thermoelectric materials. BTO should support research to investigate the potential for thermoelectric subcoolers and develop prototypes for testing; particularly those who could utilize waste heat sources, such as the compressor case.

Opportunity: The technology is applicable to residential and light-commercial A/C and HP equipment with project savings of 9% (Goetzler et al. 2012).

7.36 (ID #46) Characterize the ventilation and humidity requirements in tightly sealed buildings and investigate solutions involving automated exhaust fans in bathrooms and kitchens (Enabling)

High performance buildings specify tight building envelopes to reduce the infiltration of outside air to reduce space heating and cooling loads. While this strategy improves energy efficiency of the building, IAQ can deviate from recommended conditions without a properly designed and operating ventilation system to regulate the inlet and exhaust airflows. Kitchens and bathrooms are two key sources of humidity, smoke, and other indoor pollutants that can lead to poor IAQ for occupants. Kitchen and bathroom exhaust manufacturers have developed ventilation systems, which automatically detect motion or humidity and then activate the exhaust fan. BTO has supported research and best practices around humidity control in high performance buildings through Building America and other programs. As part of these programs, BTO should investigate the potential benefits of automated exhaust fans for bathrooms and kitchens through simulation modeling, laboratory testing, and field demonstrations. If the results are promising, the results should be disseminated amongst the building industry and incorporated into high performance building specifications and standards.

Opportunity: The technology is applicable to exhaust and ventilation systems for residential and commercial kitchens and bathrooms. Most buildings will have minimal savings, though larger opportunity may exist in commercial kitchen ventilation systems.

7.37 (ID #47) Develop occupant monitoring algorithms, set-points, and occupancy-based controls for controls by HVAC and other systems (Direct)

When configured and operated correctly, programmable thermostats reduce space conditioning energy consumption by raising or lowering temperature settings when building occupants are away. While matching HVAC operations to occupant activity in the building could offer energy savings, programmable thermostats have proven less than effective at achieving such control due to poor usability and misconceptions. To achieve this type of control, next generation thermostats and DCV systems attempt to monitor building activities through passive or automated systems such as motion detectors, CO_2 sensors, or smartphone location tracking. BTO has supported the development of advanced occupancy sensors at NREL with the Image

Processing Occupancy Sensor (IPOS). BTO should investigate the benefits of different automated and predictive control strategies through simulation modeling, laboratory study, and field demonstrations. Additionally, BTO should support efforts to ensure the identity security of building occupants from such systems through data collection and storage standards, and other means.

Opportunity: The technology is applicable to residential and commercial buildings with savings potential of 10% (Goetzler et al. 2012).

7.38 (ID #48) Develop thermal storage systems using cost-effective PCMs that activate at lower temperatures (Direct)

Thermal energy storage systems that use the latent heat of PCMs can help buffer daily temperature cycles for buildings. For example, PCMs integrated with building components (e.g., PCMs in drywall) can absorb thermal energy during the day without temperature change when melting, and then release that heat energy at night in the presence of cooler temperatures. Through this process, the A/C system operates less, particularly during the daytime when high ambient temperatures decrease efficiency and demand and/or ToU rates increase cooling costs. In recent years, BTO conducted simulation analyses by ORNL, NREL, and others into new PCMs for building envelopes and have supported several research projects to develop high-storage capacity and low-cost products. BTO should continue to support PCMs for integration with building envelope components through materials research and field demonstrations, and if promising, investigate the potential for further integration with HVAC systems.

Opportunity: The technology is applicable to residential and commercial buildings with 5–10% projected energy savings and greater cost savings (Kosny et al. 2013).

7.39 (ID #49) Develop lower cost, solar ventilation preheating systems for both wall and roof applications (Direct)

Solar ventilation preheating systems utilize transpired metal panels to capture and transfer thermal energy to air entering the ventilation system, raising its temperature. For buildings in cold-climates with large, south facing walls or roofs, solar ventilation preheating reduces the energy required to condition outside air for ventilation with only a minor increase in fan electricity consumption. The panels connect to either a packaged RTU or separate ventilation system that can supply additional heating capacity when required. In recent years, some solar PV manufacturers have started offering combined solar PV and thermal collectors (PV/T) such that the heat captured and generated by the solar PV panel provides the outdoor air preheating. DOE has supported the deployment of these systems through NREL and FEMP through field demonstrations and reporting on best practices. BTO should support the development of lower cost solar ventilation preheating systems, particularly PV/T collectors that more readily install with packaged HVAC systems.

Opportunity: The technology is applicable to residential and commercial ventilation heating. Estimated savings of 15–25% for heating (Goetzler et al. 2011).

7.40 (ID #50) Conduct teardown analysis to identify size/weight saving opportunities for packaged rooftop HVAC systems, and develop lighter-weight prototype systems (Enabling)

To achieve high efficiency performance, light-commercial RTUs typically require larger heat exchangers, which increases the weight and footprint compared to baseline equipment. For replacement applications, the contractor must consider the additional structural support, a new mounting curb, and changes to existing ductwork to accommodate the new, larger unit. The increased equipment size and weight can add cost and complexity to the installation and may pose a barrier to high efficiency RTU retrofits. DOE should reduce these operational barriers to high-efficiency RTUs by analyzing current RTU designs to identify size/weight saving opportunities, developing lighter weight components, and supporting industry collaboration to standardize RTU curb dimensions for various capacities.

Opportunity: The technology is applicable to all light commercial packaged A/C and HPs.

7.41 (ID #51) Develop a hybrid adsorption-vapor-compression HP storage unit to capture waste heat from the cycle via latent heat of evaporation from a water/zeolite mixture (Direct)

Adsorption HPs utilize porous materials that adsorb, or capture, a vapor refrigerant either on their surface or within their structure to drive a cooling cycle. When heated, these materials release the vapor at high pressure and temperature, then are cooled to accept refrigerant again. This non-continuous process of adsorption and desorption can replace an electrically driven compressor in a heat-pump cycle, or serve as a thermal battery to supplement conventional HVAC systems. When placed in a vacuum chamber with a water source, a dry zeolite material adsorbs or bonds with available water vapor, leads to further evaporation of the liquid water, producing a cooling effect until all the zeolite is saturated. In addition to generating usable cooling, heat is released as the zeolite bonds with the water. Heating the zeolite releases the water vapor, which can then be condensed and stored to repeat the cycle again.

This adsorption system can act as a thermal battery by heating the zeolite using lower-cost heat, and then generating usable heating or cooling by introducing water to the zeolite chamber at a later time. Depending on the temperature, available heat sources from HVAC, renewable, or other building systems could provide the regenerative heating to charge the thermal battery and could then provide space cooling or heating during peak hours. DOE, through the ARPA-e program, has supported the development of adsorption thermal storage for climate control systems in electric vehicles. While the thermal efficiency of adsorption systems is low compared to vapor-compression, utilizing waste or low-cost heat sources could economically offset peak HVAC demand without compromising thermal comfort. BTO should investigate the potential for adsorption and other thermal storage systems when integrated into building HVAC systems.

Opportunity: The technology is applicable to all residential and commercial HVAC systems. It has limited direct savings potential, mostly for peak demand benefits. Could offer savings if capturing waste heat.

7.42 (ID #52) Develop solid-state cooling systems (Direct)

Magnetocaloric, thermoelectric, and other solid-state cooling systems could provide efficient and cost-effective space cooling without the use of HFC refrigerants if the size, cost, weight, and performance of the specialized materials improves. DOE has supported this research through several projects including prototype development of a window A/C unit at Ames National Laboratory under the ARPA-e Building Energy Efficiency through Innovative Thermodevices (BEETIT) grant program, refrigerator development with ORNL and GE, HPWH research with Sheetak Inc., and other projects. To address these challenges, DOE should continue to support research into identifying new materials that will produce a higher temperature lift at suitable efficiency, designing advanced regenerators and heat exchangers, and other techniques to reduce the size, and ultimately cost, of the solid-state cooling plants and their accompanying systems.

Opportunity: This technology is potentially applicable to all heating and cooling applications in all climate regions. Estimated savings of 20% or greater (Goetzler et al. 2014).

7.43 (ID #53) Develop a customer-focused energy dashboard to demonstrate energy consumption and economic data from smart meters (Enabling)

As more utilities upgrade their electric metering infrastructure to digital smart meters, consumers can access their energy consumption data on an hourly, daily, and weekly level as opposed to the traditional monthly total. The utility industry, with support of DOE, has developed initiatives such as Green Button and Apps for Energy challenge to download, analyze, and visualize customer utility data in an easy-to-use and actionable format. BTO should continue to support the development of smart meter data visualization and analysis tools, such as energy dashboards for multiple computing platforms and devices, so that consumers can better understand their usage and how best to achieve energy and cost savings.

Opportunity: The technology is applicable to all residential and light commercial HVAC systems.

7.44 (ID #54) Develop low-cost chilled water storage systems (Direct)

For decades, large commercial buildings have utilized chilled water or ice thermal storage systems to reduce electrical demand from chillers during peak hours by generating thermal energy during the night. These thermal energy storage systems provide economic benefits to the building owner by using lower cost off-peak electricity and reducing monthly peak demand charges, reducing the required equipment capacity, and minimizing their net energy consumption by operating equipment during the cooler ambient temperatures during nighttime hours. While this technology is commercially available and in use for some district energy systems and large buildings, technology advances to reduce the cost and size could lead to wider application of thermal energy storage systems. BTO should support the development of advanced chilled-water and ice storage systems through materials and design advancements to increase volumetric storage capacity, reduce thermal losses, and creative integration methods with building architectures, especially for retrofits.

Opportunity: The technology is applicable to large commercial chilled water systems. Energy savings potential is expected to be 0–5%; however, peak demand reductions may reach 12–25%. Additional economic benefit can come from reduced capacity requirements (Goetzler et al. 2011).

7.45 (ID #55) Develop thermochemical energy storage systems (Direct)

Thermochemical energy storage systems utilize specialized fluids that can undergo a reverse chemical reaction to disassociate into two chemicals under an applied thermal source and then release the stored heat once recombined at a later time. Compared to other forms of energy storage such as chilled-water or ice, thermochemical systems have a high storage density and virtually unlimited storage duration making them attractive for seasonal energy storage with low-cost waste or solar thermal energy. While not commercially available, BTO and other researchers in the EU, Australia, and other countries are developing the technology for integration with large-scale solar thermal power systems. BTO should monitor the development of thermochemical energy storage systems for solar thermal power applications, and if promising, adapt the technologies for use in building HVAC systems.

Opportunity: The technology is applicable to large commercial chilled water and hot water systems with the potential for 0–5% of overall usage but could capture waste or solar heat (Goetzler et al. 2011).

7.46 (ID #56) Investigate strategies to reduce refrigerant leakage for new and existing equipment, and support development of HPs with lower refrigerant requirements (Direct)

Refrigerant leaks, common in most vapor-compression equipment over time, not only greatly reduce system capacity and efficiency, but also have detrimental effects on the environment. While this issue is most pressing for large commercial A/C and refrigeration systems, residential equipment also experiences these problems. Researchers and industry experts have developed techniques to mitigate refrigerant leakage in existing equipment through automated FDD systems to identify leakage quickly, as well as advanced tools for technicians to identify and repair leaks in the system. DOE should support the development and promotion of FDD systems that can identify refrigerant leakage for residential and commercial equipment, and support research into HP technologies and system architectures that reduce the amount of refrigerant in new equipment through the use of secondary loops or other strategies.

Opportunity: The technology is applicable to all residential and commercial vapor-compression heating and cooling technologies with savings of 5–15% by reducing refrigerant leakage (Goetzler et al. 2012).

7.47 (ID #57) Develop efficient dry-cooling techniques to replace large evaporative condensers for water savings (Direct)

Large commercial buildings commonly use evaporative cooling towers to remove heat from compressed refrigerant in chilled-water systems. While air-cooled chillers are available at low-to-moderate capacities, buildings with large chillers benefit from smaller space requirements and lower electricity usage, but subsequently tradeoff lower on-site energy use to larger water consumption. For many areas of the U.S., water is becoming both an increasingly valuable and energy-intensive resource, such that the economics and national impact of wet-cooling towers is changing. While this issue is important for HVAC systems, DOE through ARPA-e, several national labs, and in partnership with Electric Power Research Institute (EPRI) and other organizations, has supported the development of advanced dry-cooling or water-saving measures for thermal power plant heat rejection. Nevertheless, the technologies developed for large applications can impact how large chilled-water cooling systems operate. BTO should monitor the development of alternative power plant cooling technologies, and if certain technologies have applicability for HVAC systems, support their development to replaced evaporative cooling towers for chillers.

Opportunity: The technology is applicable to large chilled water systems using evaporative cooling towers. The savings is primarily in water consumption. Little energy savings is expected.

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8 Appendix D – Tier 3 Initiatives

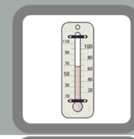
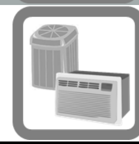
Table 8-1 lists each of the Tier 3 HVAC initiatives identified during the roadmap development process. As discussed in Section 2.3, above, Tier 3 initiatives were identified early in the process based on a first filtering of the complete list of initiatives.

Table 8-1: Tier Three Initiatives

ID	Direct/ Enabling	Activity/Initiative	Topic
58	Enabling	Develop low-cost, high-reliability wireless sensors for use in residential and commercial applications for FDD, zoning, sub-metering, etc.	FDD Controls
59	Enabling	Perform research to evaluate alternative refrigerants that maintain equivalent or better performance (split system focus)	Refrigerants
60	Direct	Develop a dehumidification system that can utilize the condensed water vapor on-site, for evaporative condenser make-up water, evaporative cooling, others.	Ventilation & Humidity
61	Direct	Develop a single-compressor, integrated building system all-in-one appliance that is built into a single pre-fab energy wall (focus on the multi-family residential sector)	Integrated Systems
62	Enabling	Perform economic research into the utility program paradigm where high efficiency is often barely above baseline; consider evaluation of efficiency over a wide operating range and how to minimize fixing old, outdated equipment in lieu of installing high efficiency new equipment.	Analysis, Education, Demonstration
63	Direct	Develop smart, variable speed equipment or other strategies to improve low-load performance (focus on high efficiencies at low capacities)	AC/HP
64	Direct	Support development of optimized components for alternative refrigerant systems	Component Development
65	Direct	Research the potential for incorporating Building Integrated HVAC Systems (GHP foundations, evaporative roof cooling, photonic Stanford system, TE cooling panels, swimming pool, large-scale outdoor heat exchangers into building architecture, especially away from the sun (e.g., north side condensers))	Component Development

ID	Direct/ Enabling	Activity/Initiative	Topic
66	Direct	Develop products and/or strategies to reduce the pressure drop in ducts, pipes, ERV, and other distribution components.	Zoning Distribution
67	Enabling	Perform research and characterize the portion of air leakage in common components, and specify low-leakage components	Zoning Distribution
68	Enabling	Develop a top-level analysis tool to provide building managers a prioritized set of faults and hierarchy of concerns as they relate to efficiency, they can then adjust accordingly	FDD Controls
69	Enabling	Conduct research to characterize customer tolerance for sensor accuracy, drift, response rate, usability, etc.	FDD Controls
70	Enabling	Develop low-cost sub-metering with intelligent feedback to operators	Tools & Software
71	Enabling	Develop a set of controls and FDD alarms that show variable grades of an alarm/fault rather than just on/off	FDD Controls
72	Enabling	Develop improved modeling tools for DHC systems	Tools & Software
73	Enabling	Enhance the capabilities of existing building energy modeling tools to more accurately model the cost and performance of variable-speed systems	Tools & Software
74	Direct	Research improved heat exchanger materials, geometry, surface treatments, etc. including ensuring long-term optimal performance	Component Development
75	Enabling	Revisit ventilation rate guidelines	Ventilation & Humidity
76	Direct	Perform basic R&D on fans and pump efficiency and the entire distribution system - Product development focus	Zoning Distribution
77	Enabling	Perform research to better understand the tradeoff between energy vs. comfort vs. IAQ for HVAC systems	Ventilation & Humidity

ID	Direct/ Enabling	Activity/Initiative	Topic
78	Enabling	Perform education outreach on the value of smart meters and smart appliances	Analysis, Education, Demonstration
79	Direct	Develop add-on humidity control package, especially for renovations where original structures were not designed for airtight seals	Ventilation & Humidity
80	Enabling	Evaluate energy savings from, and pursue development of, nighttime cooling, heating, and storage capabilities, including active & passive ventilation, PCMs, & waste heat recovery	Analysis, Education, Demonstration
81	Enabling	Conduct materials research to design motors without rare earth metals	Component Development
82	Enabling	Perform laboratory and field research to better understand the gap between as-designed and as-installed performance	Analysis, Education, Demonstration
83	Enabling	Conduct research to better understand real world impact of distribution systems to building energy consumption (including improperly designed/installed distribution systems) - Research focus	Zoning Distribution
84	Enabling	Perform research to better understand the ventilation requirements, energy consumption, and humidity impacts of tightly sealed, residential buildings	Ventilation & Humidity
85	Direct	Develop a whole-building residential FDD system that takes a holistic view on sensing and diagnostics, including energy, comfort, IAQ, performance, etc.	FDD Controls
86	Enabling	Develop a standardized efficiency metric for home HVAC systems that is simple and easy for homeowners to understand; emphasize cost and comfort	Tools & Software
87	Enabling	Analyze benefits of variable flow over fixed flow for hydronic system and develop best practice tools for existing buildings	Zoning Distribution
88	Enabling	Develop on-board FDD system for packaged HVAC systems that provides automated commissioning for systems	FDD Controls
89	Enabling	Develop standardized usability metrics for measuring the effectiveness of HVAC system interfaces	FDD Controls

ID	Direct/ Enabling	Activity/Initiative	Topic
90	Direct	Develop retrofit controllers for packaged RTUs that incorporate several advanced control techniques (e.g., DCV, VFDs, pre-conditioning, load shifting, etc.)	 FDD Controls
91	Direct	Demonstrate and promote hybrid fuel-electric HPs for cold regions	 AC/HP

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DOE/EE-1145 • October 2014