Cool Ideas: Energy-Savings Potential and RD&D Opportunities for Commercial Building HVAC Systems

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ABSTRACT

On behalf of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Program (DOE-BT), we identified and analyzed a wide range of technology options having the potential to reduce heating, ventilation, and air-conditioning (HVAC) energy consumption in U.S. commercial buildings. After a thorough literature survey, we developed a comprehensive list of 182 technology options. We selected and analyzed 57 technology options from the list to better understand each technology option's energy-savings performance, installed cost, retrofit potential, non-energy benefits, peak-demand impact, technical maturity, and next steps for development.

We scored and prioritized each of the 57 technology options according to several possible technology benefits. This yielded 17 priority technology options, each of which shows strong potential to have one or more of the following impacts:

- Provides heating or cooling more efficiently using novel technologies, strategies and/or components, or offsets energy consumption of conventional systems by optimizing performance of critical components.
- Eliminates duct leakage and/or maximizes performance of ventilation systems to significantly lower energy consumption associated with thermal distribution.
- Uses diagnostics, monitoring and evaluation to optimize and maintain efficiency of commercial HVAC systems over time.

After analyzing the priority technologies, we also recommended that DOE and industry stakeholders focus on 13 research, development and demonstration (RD&D) initiatives. These initiatives will help advance these technology options to commercialization and greater industry practice. This paper is based on Goetzler, et al. (2011), which summarizes the study commissioned by DOE-BT.

Introduction

In 2002, DOE-BT commissioned a study[1] to characterize and assess opportunities for energy savings in commercial building HVAC systems, primarily focusing on the technical energy-savings potential and current market barriers of select technology options. Since 2002, many technological improvements and building trends have changed the commercial HVAC industry, including but not limited to: improved building modeling software; the ubiquity of software-based controls; reduced cost of computing power; availability of low-cost and robust sensors; and advances in the field of material science. Furthermore, customer interest in energy

[1] Roth, et al. (2002)

efficiency has increased with greater understanding of the financial and environmental impacts for their businesses. For example, the ENERGY STAR® brand has become more widely recognized and incentive programs from utilities and government bodies have made energy-efficient solutions more viable for end-users. The HVAC manufacturing landscape has changed as well, with many foreign brands entering the U.S. market, and the growing presence of entrepreneurial start-ups offering innovative solutions across many sectors.

In light of these industry changes, the DOE-BT commissioned a new assessment of HVAC technologies for U.S. commercial buildings (Goetzler et al. 2011). The main objectives of this study were to:

- Identify a wide range of technology options in varying stages of development that could reduce commercial HVAC energy consumption;
- Provide in-depth analysis of priority technology options, including: technical energy-savings potential[2]; applicability to different building or HVAC equipment types; non-energy benefits; and perceived barriers to market adoption.
- Develop suggestions for potential research, development and demonstration (RD&D) initiatives for DOE-BT that would support further development of the most promising technology options based on potential fit with DOE-BT's RD&D portfolio, technical energy-savings potential, cost and complexity, and other factors.

Approach

We identified a wide range of technology options having the potential to reduce commercial HVAC energy consumption in U.S. buildings. This included energy-saving HVAC technology options at various stages of development, from those in proof-of-concept research to those that are widely adopted in the market. After a thorough literature survey, we developed a comprehensive list of 182 technology options, and evaluated their technical energy-savings potential and applicability to various HVAC equipment/system types. From this comprehensive list, we selected and analyzed 57 technology options to better understand each technology option's energy savings, cost/complexity, retrofit potential, non-energy benefits, potential for peak-demand reduction, technical maturity[3], and next steps for development. After establishing the scoring criteria for the second round of technology screening, we scored each of the 57 technology options based on our research and the input of HVAC experts within Navigant. Figure 1 presents the scoring matrix Navigant team used.

[2] Technical energy-savings potential is the theoretical national primary energy savings that could be achieved if all technically-suitable installations are replaced with a particular energy-saving technology. We determined the technical energy-savings potential for each technology option by combining HVAC energy-use data from US DOE (2011), US DOE (2005), and unit energy-savings estimates.

[3] Technical maturity describes the development status for the technology. Our ratings included: long-term R&D, short-term R&D, emerging, and commercially available. See Figure for technical maturity classifications of the selected priority technologies.

Figure 1. Scoring Matrix for Second Round of Technology Screening

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

For each technology option, this analysis expanded our understanding of: technical energy-savings potential and installed costs, retrofit potential, peak-demand reduction, other non-energy benefits, barriers to market adoption, and next-steps for technology development.[4]

Selected Priority Technology Options

Through this prioritization process, we identified 17 priority technology options which best fit the goals of this study. Table 1 describes four technology categories by which we grouped the options. The categories represent a top-level breakdown of the complex HVAC systems used in commercial buildings.

Table 1. Descriptions of the Technology Option Categories

Category	Energy-Savings Opportunities
Advanced Component Technologies	Optimizing the performance of critical components offsets the energy consumption of conventional HVAC systems
Alternative Heating & Cooling Technologies	Novel technologies and strategies that can provide heating or cooling more efficiently
Thermal Distribution Systems	Eliminating duct leakage and maximizing the performance of thermal distribution systems consisting of ducts
Performance Optimization & Diagnostics	Monitoring, measuring, and benchmarking the operations of the HVAC system to maintain peak performance over the life of the equipment.

Source: Goetzler et al. (2011)

The following sections describe the 17 final priority technology options with their relevant annual energy consumption[5] (AEC) in terms of Quads of primary energy[6] per year, and

[4] Refer to Goetzler et al. (2011) for summary assessments of technologies screened from final analysis.

[5] Using data combined from US DOE (2011) and US DOE (2005), relevant annual energy consumption is the sum of total U.S. primary electricity and natural gas use attributed to the characteristics of building stock (e.g., building sizes, climate zones, and equipment types) applicable for the given technology option, and multiplied by a scaling factor based on retrofit potential. Retrofit potential represents how difficult or invasive the technology might be to

estimated unit energy savings[7] (UES) in terms of percent of unit energy consumption. To determine technical energy-savings potential, we multiplied the UES by the AEC attributed to the technology option.

Advanced Component Technologies

Table 2 summarizes the two technology options that fall under the Advanced Component Technologies category.

Table 2. Summary of Advanced Component Technology Options

Category	AEC (Quads/yr)	UES	Descriptions
Smart Refrigerant Distributors	0.98	9%	Refrigerant maldistribution in evaporators lowers capacity and efficiency. Smart refrigerant distributors sense and direct proper amounts of refrigerant to each evaporator circuit, maintaining optimum performance.
Thermoelectrically Enhanced Subcooling	2.25	9%	Thermoelectric (TE) devices convert electricity to a thermal gradient that can provide efficient cooling for small temperature lifts or cooling loads. A subcooler incorporating TE stages lowers the temperature of condensed refrigerant and raises overall system capacity and coefficient of performance.

Source: Goetzler et al. (2011)

implement in existing buildings, and was scored on a High/Medium/Low basis. These scores correspond to a scaling factor of 100%, 50%, and 5%, respectively.

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

[7] Unit energy savings reflects our conservative estimate of a technology option’s percent energy savings when compared to a baseline technology typically used in U.S. commercial buildings, as determined from published literature.

Alternative Heating & Cooling Technologies

Table 3 summarizes the six technology options that fall under the Alternative Heating & Cooling Technologies category.

Table 3. Summary of Alternative Heating & Cooling Technology Options

Category	AEC (Quads/yr)	UES	Descriptions
Liquid Desiccant Air-Conditioning	1.07	20%	For humid regions with small sensible heating loads, liquid desiccant air conditioners can remove latent heat more efficiently than vapor-compression systems. The liquid desiccant absorbs moisture from the incoming air, lowering the supply air-temperature entering the building. A regenerator heats the desiccant, exhausting the moisture, which allows the cooling cycle to continue.
Magnetic Cooling Cycle	0.91	17%	The magnetic cooling cycle provides cooling through magnetocaloric effect, a phenomenon where certain materials undergo temperature change when exposed to a changing magnetic field. Although limited by the current state of materials science with permanent magnets, this solid-state cooling technology could provide energy savings and other advantages over conventional systems.
Solar Enhanced Cooling	0.11	90%	Using solar radiation, solar enhanced cooling technologies heat water to drive thermally activated cooling systems such as absorption or liquid-desiccant systems. By providing a low-cost source of medium-grade heat, this technology significantly lowers the primary energy use of thermally activated systems, improving their economics when compared to conventional vapor-compression systems.
Solar Ventilation Preheating	0.99	11%	Solar ventilation preheating systems use transpired collection panels to absorb solar radiation and transfer heat to ventilation air. This process offsets the use of natural gas or electricity to raise the ventilation air temperature to suitable building conditions during the heating season.
Thermoelectric Cooling Cycle	1.13	33%	Under an applied voltage, thermoelectric (TE) cooling systems create a cooling effect using the specialized TE materials. This solid-state technology may become highly efficient once fully mature, but it requires additional long-term research to increase the performance of the current TE materials.
Thermotunneling Cooling Cycle	1.13	9%	Thermotunneling cooling system is an advanced form of thermoelectric cooling that transmit electrons across a vacuum gap to obtain cooling and heating. Although modeling has shown large potential energy savings, this solid-state technology requires additional long-term research to solve a number of technical concerns.

Source: Goetzler et al. (2011)

Thermal Distribution Systems

Table 4 summarizes the five technology options which fall under the Thermal Distribution Systems category.

Table 4. Summary of Thermal Distribution Systems Technology Options

Category	AEC (Quads/yr)	UES	Descriptions
Aerosol Duct Sealing	6.69	9%	When introduced in duct systems, aerosol duct sealants deposit around air holes, plugging leaky ducts without having to locate them first. By decreasing the losses associated with duct leakage, a greater percentage of the thermal energy reaches its intended space, reducing thermal and fan energy consumption.
Demand-Controlled Ventilation	0.94	10%	Demand-controlled ventilation (DCV) eliminates excessive outdoor airflow when building occupancy falls below peak-design levels. By providing the required amount of ventilation based on actual occupancy, DCV maintains suitable indoor air quality while consuming less energy.
Duct-Leakage Diagnostics	4.03	7%	Leakage in commercial HVAC duct systems wastes energy associated with fan usage and thermal conditioning. Diagnostic testing methods such as the pressurization, Delta Q, or tracer gas test alert building operators of the presence of leaks so they may be repaired.
Ductwork in Conditioned Space	2.40	10%	Ductwork placed outside of the building envelope can lose significant amounts of energy through thermal and airflow losses. HVAC equipment must often provide additional output to overcome these losses, or risk under-conditioning the spaces. Placing ductwork within the conditioned space either through initial system design, duct relocation, or extending the thermal barrier to include ductwork, reduces the impact of duct leakage on system efficiency.
Thermal Displacement Ventilation	1.71	10%	Thermal displacement ventilation systems supply low-velocity, conditioned air close to the floor that rises through natural convection to a return vent near the ceiling. The vertical airflow improves indoor air quality and comfort by displacing pollutants and stale air to the ceiling, away from occupants.

Source: Goetzler et al. (2011)

Performance Optimization & Diagnostics

Table 5 summarizes the four technology options which fall under the Performance Optimization & Diagnostics category.

Table 5. Summary of Performance Optimization & Diagnostics Technology Options

Category	AEC (Quads/yr)	UES	Descriptions
Retrocommissioning	6.69	13%	HVAC systems in commercial buildings often operate less efficiently than designed due to equipment deterioration, inadequate maintenance, or improperly operated controls. Retrocommissioning (RCx) restores building performance by investigating, evaluating, and repairing the HVAC system and its operations through a systematic process.
Continuous Commissioning	0.94	17%	Continuous commissioning (CC) is a periodic process that collects data from building HVAC systems, compares with previous operational data, and reports where dropping performance occurs. By evaluating the actual building conditions and energy consumption over time, CC detects system faults and directs maintenance to restore efficiency.
Building Energy Information System	4.00	20%	Building Energy Information Systems (EIS) are suites of technology solutions that store, analyze, and display building energy data acquired through energy performance monitoring. This data helps facility managers and other end-users identify opportunities for efficiency improvements.
Packaged Rooftop Air Conditioner Fault Detection and Diagnostics	0.63	13%	Fault detection and diagnostic (FDD) systems alert building operators of common problems associated with packaged rooftop HVAC systems. By identifying performance deviation and determining its cause, directed maintenance can restore the equipment to peak efficiency.

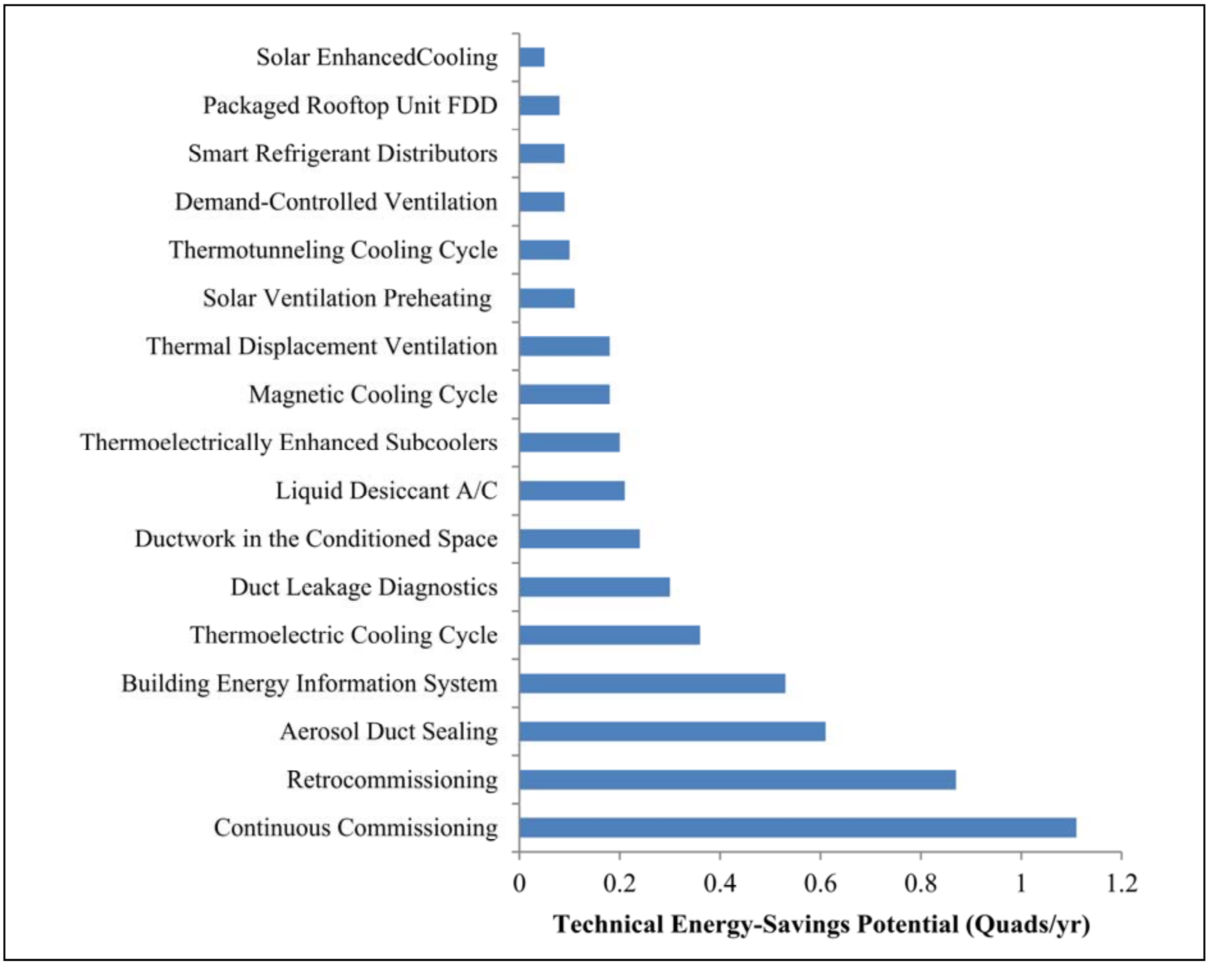
Source: Goetzler et al. (2011)

Potential Energy Savings and Non-Energy Benefits

As Figure 2 illustrates, each of the 17 priority technology options offers significant technical energy-savings potential. In some cases, multiple technology options target the same savings opportunity through different approaches, e.g., Retrocommissioning and Continuous Commissioning. For these technology options, the technical energy-savings potentials are not additive.

In addition to reducing energy consumption, many of the priority technology options selected for in-depth analysis feature non-energy benefits as well. Common non-energy benefits included: improved occupant comfort, improved indoor air quality, reduced equipment size, reduced noise, reduced maintenance needs, extended equipment life, and reduced refrigerant charge. These additional benefits provide both qualitative and quantitative value to building owners and occupants. In many instances, the non-energy benefits may be more important than energy savings.

Figure 2. Technical Energy-Savings Potential for the 17 Priority Technology Options



Source: Goetzler et al. (2011)
Note: Potential savings are not additive for most technology options and applications. To determine technical energy-savings potential, we multiplied the estimated unit energy savings (UES) percentage by the annual energy consumption (AEC) attributed to the technology option.

Comparison to 2002 Study

As mentioned above, DOE-BT commissioned a similar study in 2002 (Roth et al. 2002). Observed differences in the commercial HVAC market as well as differences in the evaluation of technology options led to changes between the 2002 study and the 2011 study.

One difference between the current study and the 2002 study is that our screening criteria considered a technology option's fit with DOE-BT's mission, whereas the 2002 study did not. This led us to choose some technology options for the in-depth analysis that the 2002 study screened out. On the other hand, we determined that some technology options that the 2002 study analyzed in depth are either widely adopted today, would not benefit significantly from future DOE involvement in its development, or both. Either case would suggest that these technology options are a poor fit with DOE-BT's mission, and, therefore, we screened them out. Table 6 compares the technology options analyzed in detail in the current study to those analyzed in detail in the 2002 study.

Table 6. Comparison of Final Technology Options Analyzed in 2002 and 2011 Studies

Technology Option Category	Included in Goetzler et al (2011)	Included in Roth et al (2002)
Advanced Component Technologies	- Smart Refrigerant Distributors - Thermoelectrically Enhanced Subcoolers	- Electrically-Commutated Motors - Enthalpy/Energy Recovery Heat Exchanger - Microchannel Heat Exchangers - Small Centrifugal Compressors
Alternative Heating & Cooling Technologies	- Liquid Desiccant A/C - Magnetic Cooling Cycle - Solar Enhanced Cooling - Solar Ventilation Preheating - Thermoelectric Cooling Cycle - Thermotunneling Cooling Cycle	- Liquid Desiccant A/C - Dedicated Outdoor Air Systems - Cold-Weather Heat Pump - Radiant Ceiling Cooling/Chilled Beam - Variable Refrigerant Volume/Flow
Thermal Distribution Systems	- Aerosol Duct Sealing - Demand-Controlled Ventilation - Duct-Leakage Diagnostics - Ductwork in Conditioned Space - Thermal Displacement Ventilation	- Aerosol Duct Sealing - Thermal Displacement Ventilation - Microenvironment - Thermal Energy Storage
Performance Optimization & Diagnostics	- Building Energy Information System - Continuous Commissioning - Packaged RTU FDD - Retrocommissioning	- System/Component Diagnostics[a] - Adaptive and Fuzzy Logic Control

[a] This technology covered many of the performance optimization technologies that were analyzed in Goetzler et al. (2011)

The differences between the two lists reflect the maturation of several older technologies and the introduction of new technologies and prototypes into the market.

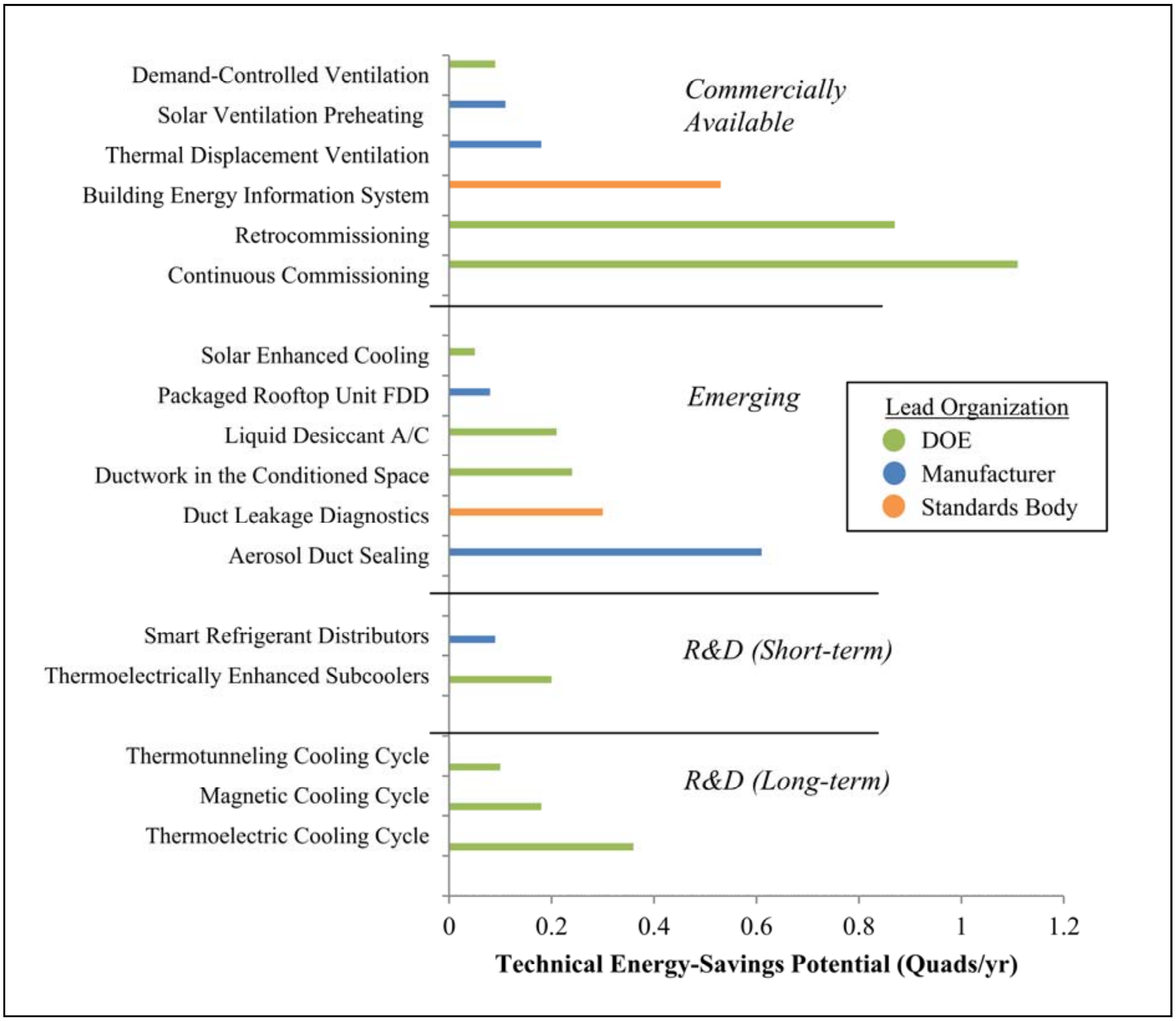
Recommended Technology Development Initiatives

One of the objectives of this study was to develop suggestions for potential RD&D initiatives to support further development of the analyzed technology options. Advancing these technology options to commercialization and greater industry practice will reduce commercial HVAC natural gas and electricity consumption in the U.S. For each initiative, we focused on determining the potential fit with DOE BT's RD&D portfolio while identifying other key stakeholders.

We assume that DOE, in conjunction with other stakeholders, will have a large role in supporting basic research and development of immature technologies, while manufacturers and industry organizations, i.e., standards bodies, will have primary roles in demonstrating, refining, and supporting emerging and available technologies.

Based on our review of the 17 priority technology options, we recommend that DOE and industry stakeholders focus on the initiatives listed below. Figure 3 lists the 17 priority technology options, sorted by technical maturity and designated with one of three lead organizations.

Figure 3. Recommended Lead Organizations for Advancement of the 17 Priority Technology Options



Source: Goetzler et al. (2011)

While we suggest a lead organization for each initiative, many of these initiatives will require collaboration among the various industry stakeholders, including building owners. For mature technology options, we suggest that DOE has a role in developing resources for collecting and sharing of information, in funding research of further design options, and in shaping incentive programs. We also suggest that manufacturers, industry organizations, and utilities have an equally large role in shaping the development of these technology options. For systems based on sensor technology and software, we see development of consensus standards as the greatest need, and this is most appropriate for standards bodies.

Based on our review of the 17 priority technology options, we recommend that DOE and industry stakeholders focus on the 13 initiatives summarized in Table 7. Specific recommendations for each priority technology option are listed in their corresponding write-up in Goetzler, et al. (2011).

Table 7. Recommended Initiatives for the 17 Priority Technology Options

Recommended Lead Organization	Recommended Initiatives	Applicable Technology Options
DOE (R&D-Stage Technology Options)	Support development of advanced high-ZT[8] materials and low work-function materials	- Thermoelectric Cooling Cycle - Thermoelectrically Enhanced Subcoolers
	Support development of designs reducing the use of rare-earth metals Support development of improved manufacturing strategies for small-scale, advanced-material technologies	- Magnetic Cooling Cycle - Thermoelectric Cooling Cycle - Thermoelectrically Enhanced Subcooler - Thermotunneling Cooling Cycle
DOE (Emerging and Commercially Available Technology Options)	Conduct long-term field studies on alternative ventilation strategies	- Demand-Controlled Ventilation - Thermal Displacement Ventilation
	Support development of strategies to facilitate assessment of airflow and thermal efficiency of ducts	- Aerosol Duct Sealing - Duct-Leakage Diagnostics - Ductwork in the Conditioned Space
	Support further refinement of the energy economics for performance optimization and diagnostics technologies Develop greater understanding of real-world energy performance for HVAC equipment and systems over their lifetime	- Building Energy Information System (EIS) - Continuous Commissioning - Packaged Rooftop Unit Fault Detection and Diagnostics (FDD) - Retrocommissioning
Manufacturers	Develop techniques for cost-effective integration of component technologies into existing systems Conduct demonstrations of, and publish field data for, advanced components using a variety of refrigerant types and equipment designs	- Smart Refrigerant Distributors - Thermoelectrically Enhanced Subcoolers
	Optimize the capabilities, and number, of sensors for performance optimization and diagnostics systems	- Building EIS - Continuous Commissioning - Packaged Rooftop Unit FDD - Retrocommissioning
Industry Trade Organizations	Incorporate duct-leakage prevention and best practices into future building standards and codes	- Aerosol Duct Sealing - Duct-Leakage Diagnostics - Ductwork in the Conditioned Space
	Establish industry standards for fault detection and diagnostics systems	- Building EIS - Continuous Commissioning - Packaged Rooftop Unit FDD
Utilities	Offer incentives to decrease the upfront costs of performance optimization and diagnostics systems, or support pilot demonstration projects for emerging technologies.	- Building EIS - Continuous Commissioning - Packaged Rooftop Unit FDD - Retrocommissioning

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[8] ZT is a dimensionless figure-of-merit that describes the effectiveness of a thermoelectric material.

References

Note: For additional information (including references) for each technology option, refer to Goetzler, et al. (2011).

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