U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

High-Impact Technology Catalyst

2017 Prioritization Analysis

June 2017

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Preface

The Department of Energy's (DOE) Building Technologies Office (BTO), a part of the Office of Energy Efficiency and Renewable Energy (EERE) engaged Navigant Consulting, Inc., (Navigant) to update the strategic plan for the High-Impact Technology Innovation (HIT) Catalyst program.

This document serves as an overview of the HIT Catalyst identification, analysis, and prioritization activities for 2017, including a summary of the selection process BTO used to prioritize the current HITs and descriptions of the current technical and market landscapes for each HIT. BTO plans to update this document in 2018 to reflect changes in the technical landscape for existing HITs and to incorporate new strategic research and development priorities. Based on 2017 analysis, the HIT team chose to retain the 6 existing HIT priority areas in this document and did not add any new HITs.

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List of Acronyms

ACEEE	American Council for an Energy Efficient Economy
AERC	Attachments Energy Rating Council
AFDD	Automated Fault Detection and Diagnostics
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AHU	Air-Handling Unit
APS	Arizona Public Service
BAS	Building Automation Systems
BBA	Better Buildings Alliance
BEMOSS	Building Energy Management Open-Source Software Development
BMS	Building Management System
BOMA	Building Owners and Managers Association
BPA	Bonneville Power Administration
BTO	Building Technologies Office
CBECS	Commercial Buildings Energy Consumption Survey
CBEI	Consortium for Building Energy Innovation
CBERD	Center for Building Energy Research and Development
CBI	Commercial Buildings Integration
CCHP	Cold-Climate Heat Pump
CEE	Consortium for Energy Efficiency
CGDB	Complex Glazing Database
COP	Coefficient of Performance
DLC	Design Lights Consortium
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EER	Energy Efficiency Ratio
EERE	Energy Efficiency and Renewable Energy
EIS	Energy Information System
EMIS	Energy Management and Information System
EMS	Energy Management System
EPA	U.S. Environmental Protection Agency
ERV	Energy Recovery Ventilator
ESTCP	Environmental Security Technology Certification Program
ET	Emerging Technologies (Program)
FDD	Fault Detection and Diagnostics
FEMP	Federal Energy Management Program
FY	Fiscal Year
GHG	Greenhouse Gas
GPG	Green Proving Ground
GSA	U.S. General Services Administration
GWP	Global Warming Potential
HFC	Hydrofluorocarbon
HIT	High-Impact Technology
HVAC	Heating, Ventilation, and Air Conditioning
IES	Illuminating Engineering Society
IFMA	International Facility Management Association

IGDB	International Glazing Database
ILC	Interior Lighting Campaign
IOU	Investor Owned Utility
IT	Information Technology
kW	Kilowatt
kWh	Kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LED	Light-Emitting Diode
LEED	Leaders in Energy and Environmental Design
LEEP	Lighting Energy Efficiency in Parking
LUMEN	Lighting Utility Midwest Exchange Network
M&V	Measurement and Verification
NEEA	Northwest Energy Efficiency Alliance
NEEP	Northeast Energy Efficiency Partnerships
NREL	National Renewable Energy Laboratory
NYPA	New York Power Authority
NYSERDA	New York State Energy Research and Development Authority
O&M	Operations and Maintenance
ORNL	Oak Ridge National Laboratory
PG&E	Pacific Gas and Electric
PIER	Public Interest Energy Research Program
PNNL	Pacific Northwest National Laboratory
P-Tool	Prioritization Tool
R&D	Research and Development
REEO	Regional Energy Efficiency Organizations
RFI	Request for Information
RMI	Rocky Mountain Institute
RTEM	Real Time Energy Management
RTU	Rooftop Unit
SCE	Southern California Edison
SEEA	Southeast Energy Efficiency Alliance
SMUD	Sacramento Municipal Utility District
SNAP	Significant New Alternatives Policy
SPEER	South-Central Partnership for Energy Efficiency as a Resource
SSL	Solid-State Lighting
TBtu	Trillion British Thermal Units
TLED	Tubular or Troffer LED
TWh	Terawatt-hour
USGBC	United States Green Building Council
UTRC	United Technologies Research Center
VRF	Variable Refrigerant Flow
WCMA	Window Covering Manufacturers Association
WHPA	Western HVAC Performance Alliance
ZNE	Zero Net Energy

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1 Introduction and Purpose

The High-Impact Technology Innovation (HIT) Catalyst was initiated by the U.S. Department of Energy's (DOE) Commercial Buildings Integration (CBI) program to identify cost-effective, innovative building technologies with large energy savings and adoption potential, and to focus programmatic activities on the integration of these technologies into new and existing buildings. In addition, the HIT Catalyst aligns CBI's technology-specific activities under a single, cohesive strategic framework.

The energy savings opportunity in commercial buildings varies according to building type, systems, climate zone, construction type, and occupant density, among other factors. To translate this complexity and opportunity into actionable, strategic approaches, DOE's Building Technologies Office (BTO) conducts a research, identification, and evaluation exercise. This exercise compiles and analyzes technologies that can make the most impact in achieving BTO's energy savings goals, high-impact technologies, or HITs. HITs are prioritized based on key quantitative and qualitative criteria to generate a priority list, the "HIT List."

The HIT Catalyst program operates cyclically. Each year, the HIT Catalyst program closes out completed HIT activities, adds new HITs, reevaluates existing HITs, and starts new or improves existing activities where needed (or hands off those activities to external organizations for continuation). Table 1 discusses the annual efforts.

Table 1. HIT Catalyst Annual Cycle

Stage	Action Steps	Ongoing Activities (Year-Round)
Technology Identification	• Initiate request for information (RFI) to gather suggestions on new candidate HITs (as needed) • Conduct literature and market review on possible new HITs, including new Scout (formerly Prioritization-Tool) measures and "graduates" of other technology research and development (R&D) programs (Tech Sweep) • Add new inputs to the HIT Matrix • Use BTO Peer Review, Better Buildings Technical Research Teams, and other partner networks to review and provide HIT Catalyst program feedback	• Catalog data and suggestions on possible HITs for next cycle • Initiate new programmatic activities • Reevaluate plans for existing HITs and assess possible next steps upon activity completion • Hand off HITs once research, development and validation is complete
HIT Prioritization	• Conduct workshops to answer qualitative questions, understand changing technical and market conditions and uncover work by others • Refresh HIT selection matrix with workshop feedback • Revisit HIT priority list based on HIT Matrix updates • Develop HIT Watch List based on new high-potential areas of work	
Strategic Planning	• Develop technology-specific plans for new HITs (as applicable for new technologies) • Update existing HITs based on new technical and market conditions	

Source: Based on DOE internal strategy.

This document serves as an overview of the selection process CBI used to identify, evaluate, and prioritize the current HITs, descriptions of the technologies, and markets for each HIT. CBI revises this document each year to reflect changes in DOE priorities, in the technical and market landscape as well as to prepare and initiate programmatic planning for new HITs. In any given year, BTO may determine that the existing HITs require continued focus and may not initiate activities for new HITs to ensure sufficient resources for existing HITs.

In 2017, the HIT team updated the six existing HITs in this document based on technical advancements and changes in the market and did not add any new HITs. Section 2.2 contains a list of 15 technologies identified and prioritized for inclusion on a Watch List, for future consideration. Additionally, in 2017, the team began exploring more focused work on HITs for new construction; the initial analysis is documented in Section 10.

2 HIT Background and Selection Methodology

2.1 HIT Selection Methodology

DOE's initial list of candidate technologies was drawn from a thorough literature review (the Tech Sweep) and from the BTO Prioritization Tool (P-Tool, or Scout[1]). CBI developed a spreadsheet model, the HIT Matrix, to track the potential energy savings impacts of all the identified energy efficiency technologies. Technology descriptions and energy savings potential values were migrated from the P-Tool to seed the HIT Matrix and were augmented with additional technologies from supplementary channels, including the Tech Sweep. In total, CBI evaluated more than 400 candidate technologies for 2017.

CBI organized the HIT Matrix using two screens to gauge technical energy savings potential, private sector activity, cost, and manufacturing readiness and capacity. This technology evaluation ensures that BTO can affect structured plans based on specific technology requirements. Figure 1 depicts the technology screening process.

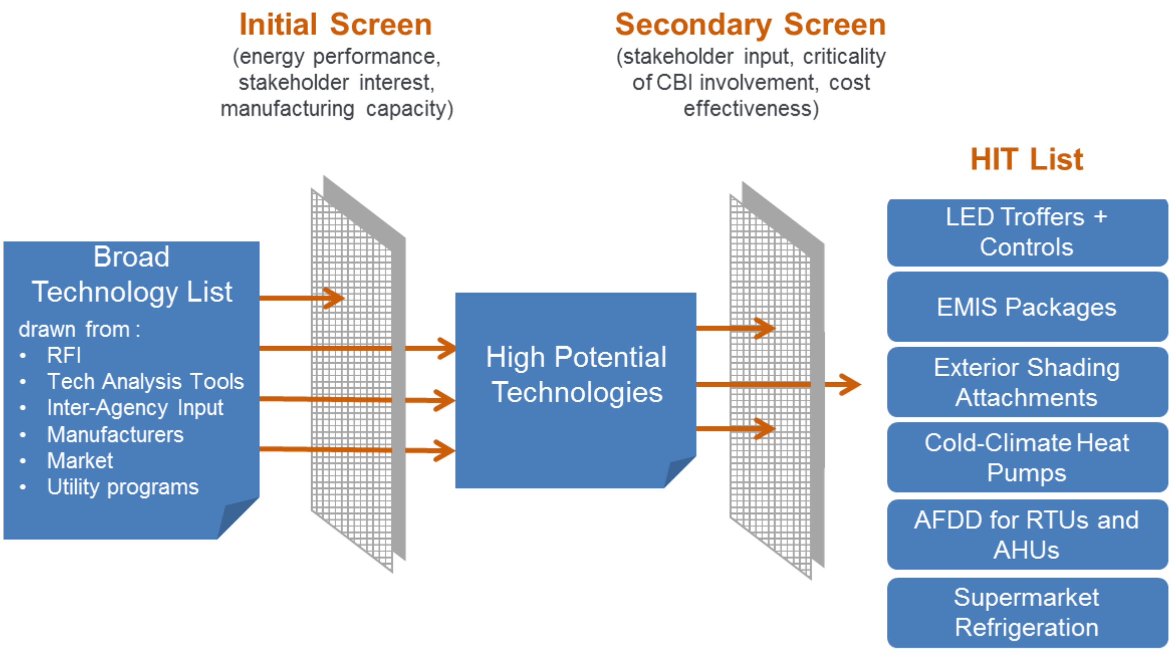

Figure 1. HIT technology screening overview

Source: Based on DOE internal strategy

[1] Scout, the successor to the BTO Prioritization Tool, is under active development. For more information, see the Scout tool homepage, https://energy.gov/eere/buildings/scout. For updates on Scout progress, see https://github.com/trynthink/scout/wiki.

2.1.1 Technology Evaluation Criteria

Several criteria were used to characterize the candidate technologies and develop the initial outputs of the HIT selection process, depicted in Table 2. The criteria used in the first screen are largely quantitative and are used to eliminate technologies inappropriate for the program. The criteria in the second screen were evaluated during workshops with subject matter experts to rank the technologies based on qualitative factors for further consideration.

Table 2. HIT Screening Factors

	First Screening Stage	Second Screening Stage
Evaluation Criteria	• Significance of unit savings potential • Significance of national savings potential • Specificity of measure[2] • Technology readiness • Alignment with HIT program methodology	• Criticality of CBI involvement • Existing manufacturing capacity • Current cost-effectiveness • Cost reduction potential

Source: Based on DOE internal strategy.

2.1.2 HIT Matrix

The HIT List is developed using the HIT Matrix, an Excel-based tool created for use in categorizing and sorting the data for each candidate technology. The HIT Matrix includes information for each technology in the following key areas:

- Technology description and overview
- Technology area (end-use sector)
- Per-unit and national technical energy savings potential (drawn from the P-Tool/Scout and Tech Sweep)
- Estimates of technology readiness and appropriateness for the HIT program[3]
- Quantification of the status of key factors (as described in previous section)
- Discussion of existing CBI efforts focused on the technology.[4]

The HIT Matrix allows for CBI to continually grow its database of known technologies and associated attributes as new technology or technology research areas and supporting data arise from literature review, RFI responses, stakeholder workshops, and other channels. It is a living document that can be easily updated in real time as new information becomes available. This tool also provides a mechanism for sorting HITs based on their technical energy savings potential, market factors, relevant end-use sector, and other key areas. The sorted list of HIT Matrix entries is used as the basis for final discussion and selection of HITs.

In future evaluation cycles, the HIT Matrix will reflect new data available from Scout and commercial stock analysis, which can be used to prioritize measure integration and optimization research priorities.

[2] To be considered as actionable within the HIT framework, a technology must be defined with sufficient specificity to allow a quantitative assessment of the market potential, barriers, and deployment steps to be performed. Measure groupings that are too broad to allow this are generally broken down until a workable level of granularity is achieved.

[3] Appropriateness depends on work by others. In cases where BTO can leverage this work, this informs activity planning. In other cases, work by others may be sufficiently broad that a BTO role is unnecessary.

[4] Activities may include work with utilities, trade associations (such as ASHRAE, IES of North America, or USGBC), regional energy organization and nonprofits as well as the activities of the Better Buildings Technology Research Teams, https://www4.eere.energy.gov/alliance/.

2.1.3 Stakeholder Workshop Process

In an ongoing fashion, BTO collects comprehensive technology inputs and feedback through existing stakeholder networks, such as the Better Buildings Technology Research Teams, state and local governments, consultants, and utility groups. The HIT Catalyst program is discussed at the annual BTO Program Review, and HITs are emphasized as part of the Better Buildings Summit technology tracks.

A key component of the HIT prioritization process is the facilitation of discussions among stakeholders from both within the CBI Program and from many external organizations. These meetings allow the program to solicit specific feedback on the HIT Catalyst methodology, candidate technologies, and other programs underway in key commercial building technology sectors. As part of the development process for the 2017 HIT List, CBI hosted several webinars with major stakeholders, as well as in-person meetings to solicit feedback from federal entities. Table 3 shows a list of participants in the workshop process.

Table 3. 2017 HIT Update Process Workshop Participants

Workshop Participants		
Seventhwave	Better Buildings Partners	Northeast Energy Efficiency Partnership (NEEP)
ARPA-E	Energy Solutions	New York Power Authority (NYPA)
Bonneville Power Administration (BPA)	Ever Source	Rocky Mountain Institute (RMI)
CBRE	U.S. General Services Administration (GSA)	Southeast Energy Efficiency Alliance (SEEA)
CEG Solutions	National Grid	South-Central Partnership for Energy Efficiency as a Resource (SPEER)
Con Edison	Navigant	DOEs

Source: Results of outreach by DOE CBI, DOE National Laboratories, and Navigant.

These workshops provided a broad perspective on the various technologies under consideration and in shaping the final HIT list. Going forward, CBI plans to continue and expand these discussions as part of the annual HIT prioritization process.

Based on the HIT List, BTO convenes ongoing technology-specific discussions to continually improve its understanding of the market landscape for that technology, uncover specific barriers or challenges, and to identify promising areas of work that could meet energy savings goals.

2.2 Selected HITs

For the 2017 HIT Catalyst program, six HITs were prioritized for continued focus. The HIT List for 2017 includes:

- Light-emitting diode (LED) troffers with controls (ongoing from 2015)
- Energy management and information systems (EMISs) and building diagnostics and controls (ongoing from 2015), including:[5]
    - Automated fault detection and diagnostics (AFDD)
    - Submetering
    - Monitoring-based commissioning

[5] Throughout this document, this broad technology area will be referred to as EMIS.

  - Automated System Optimization
- Envelope attachments (ongoing from 2015)
- Cold-climate heat pumps (CCHP) (ongoing from 2016)
- AFDD systems and controls for rooftop units (RTUs) and air handling units (AHUs) (ongoing from 2016)
- Advanced supermarket refrigeration systems (ongoing from 2016)

Additionally, this report includes a new section describing the potential for HITs to substantially impact commercial building energy consumption by targeting new construction applications. CBI regularly discusses HITs and other technologies with building community members, many of which are focused on the high-performance and zero-net-energy (ZNE) new construction market. Section 10 provides additional details on the potential benefits of HITs for new construction commercial buildings.

Table 4 through Table 9 provide specific details about each of the HIT measures and the outcomes of the HIT prioritization process. The tables include estimates of the national technical energy savings potential for each technology, along with qualitative assessments weighted on a 1-3 scale, with 3 being the highest level of opportunity or need. The data included in these tables represents the aggregate results developed from the HIT matrix and stakeholder workshops.

The tables also describe the peak demand impact potential of the technology beyond the baseline energy reduction offered through implementation of the measure. This takes the form of a preliminary, qualitative characterization of the impact potential. In later studies, CBI plans to incorporate more quantitative information on peak demand impact potential and grid responsiveness through analysis using Scout and other tools. The qualitative descriptors used now are:

- **Significant benefit**: The technology has the potential to significantly decrease building energy consumption at peak-demand periods.
- **Moderate benefit**: The technology has the potential to decrease building energy consumption at peak-demand periods.
- **Neutral**: The technology will produce peak demand reduction levels commensurate with the overall average energy benefit of the technology; technology performance does not disproportionately fluctuate at peak-demand periods.
- **Negative benefit**: The technology may experience higher energy consumption during peak load periods, generally corresponding to most adverse ambient conditions.

Table 4. LED Troffers with Controls – Overview

Description	High-efficiency (solid state) troffers with integrated controls.		
National Primary Energy Savings Potential	Stakeholder Interest	Criticality of DOE Involvement	Cost-Effectiveness and Reduction Potential
500-1,000 Trillion TBtu Estimated annual energy savings if all existing fluorescent troffers were switched to LED troffers w/ controls.	3.0 Stakeholders understand the high energy and cost savings potential is attainable through lighting retrofits.	2.0 Many efforts on LED lighting exist, DOE can support additional performance improvement and better “plug & play” integration.	2.0 Solid-state lighting (SSL) prices are currently on a downward trajectory, and further decreases are expected.

Peak demand impact potential: moderate benefit	

Table 5. Energy Management and Information Systems / Whole Building Diagnostics –Overview

Description	Validate the performance and functionality of EMIS and whole building diagnostic or automation tools. Continue research into opportunities that ease connection and automation of additional components and systems. These systems encompass a broad family of tools and services to manage commercial building energy use including energy information systems (EIS), equipment-specific fault detection and diagnostic (FDD) systems, benchmarking and utility tracking tools, automated system optimization (ASO), and building automation systems (BAS).		
National Primary Energy Savings Potential	Stakeholder Interest	Criticality of DOE Involvement	Cost-Effectiveness and Reduction Potential
1,000+ TBtu Estimated annual energy savings if all commercial buildings adopted advanced EMSs/EMISs.	2.0 CBI efforts focusing on EMISs to date have drawn significant interest from building owners.	3.0 Most offerings are focused on HVAC systems but there is a strong opportunity for DOE to support current R&D through validation and identify gaps in functionality.	2.5 Systems can currently achieve desirable paybacks; however significant energy savings is available with sophisticated autonomous, learning, or adaptive whole building applications.
Peak demand impact potential: Significant benefit			

Table 6. Attachments – Overview

Description	Validate energy use reduction and other benefits arising from the use of optimized static attachments and dynamic window attachments to manage solar gain and daylight.		
National Primary Energy Savings Potential	Stakeholder Interest	Criticality of DOE Involvement	Cost-Effectiveness and Reduction Potential
500-1,000 TBtu Estimated annual energy savings if all applicable commercial buildings employed shading elements.	2.0 Participants in the DOE workshops and stakeholder meetings have expressed significant interest.	2.0 This technology is mature globally but not cost effective in the U.S.	2.5 Significant opportunities exist to bring down costs.
Peak demand impact potential: Significant benefit			

Table 7. Cold-Climate Heat Pumps (CCHP) – Overview

Description	Validate the performance potential of commercial-scale heat pumps for use in cold climates where electric resistance heating has traditionally been employed.		
National Primary Energy Savings Potential	Stakeholder Interest	Criticality of DOE Involvement	Cost-Effectiveness and Reduction Potential
500-1,000 TBtu Estimated annual energy savings attributable to complete displacement of electric resistance heating in relevant commercial applications.	3.0 Stakeholders have exhibited significant interest in this technology, particularly in regions with large heating loads and use of electric resistance heat.	3.0 There has been limited field testing of these units in commercial settings in the United States.	2.0 Continued evolution of the technology is needed to improve paybacks for commercial heat pumps in cold climates could become attractive.
Peak demand impact potential: Neutral			

Table 8. AFDD Systems for RTUs and AHUs – Overview

Description	Study the integration and effectiveness of aftermarket AFDD packages for existing rooftop heating, ventilation, and air-conditioning (HVAC) units and AHUs, as well as factory-installed options for new equipment.		
National Primary Energy Savings Potential	Stakeholder Interest	Criticality of DOE Involvement	Cost-Effectiveness and Reduction Potential
1,000+ TBtu Estimated annual energy savings possible through installation and use of retrofit AFDDs controls for existing RTUs and AHUs.	2 Stakeholders are aware of the technology.	3 DOE could serve a key role in helping to differentiate and disseminate useful field data regarding existing applications and gaps.	2.5 AFDD packages are cost effective before integration and commissioning. Research is needed on whether integration within existing units or within larger whole building energy management systems can be cost-effective and create persistent savings.
Peak demand impact potential: Significant benefit			

Table 9. Advanced Supermarket Refrigeration Systems – Overview

Description	Research and validate advanced technologies for supermarket refrigeration systems.		
National Primary Energy Savings Potential	Stakeholder Interest	Criticality of DOE Involvement	Cost-Effectiveness and Reduction Potential
100-500 TBtu Benefits for energy efficiency, refrigerant leakage reduction, reduced operations and maintenance (O&M), and lower global warming potential (GWP) impact.	3 Supermarkets are a low margin business, so technologies that cost-effectively improve the performance and efficiency of refrigeration systems have significant interest.	3 DOE could provide independent field study data regarding equipment performance.	1.5 Costs are currently high, and some aspects of the technology are inherently expensive.
Peak demand impact potential: Neutral to negative benefit			

3 Overview of Technology-Specific Analysis

Section 4 through Section 9 contain the respective landscape summaries for each of the six HITs. These sections lay out available information for the technology at the time of its selection as a HIT. Each of these sections include the following technology-specific information:

- A landscape summary, including:
  - Discussion of key sectors and applications for the technology
  - Major manufacturers and suppliers of the HIT
  - Relevant DOE CBI work to date
  - Technical and structural barriers
  - A summary of programs and external efforts outside of CBI focusing on the technology
- A discussion of opportunities for technical investigation, research, product integration advancement and/or field study, i.e. the identification of performance metrics, activities related to gaps in research, development to ease component or system integration, commissioning, and whole building energy optimization; data collection in the laboratory or in the field to answer critical research questions.

CBI works partnership with GSA's GPG program via the HIT Catalyst. This collaboration includes independent validation by the DOE national laboratories for private sector technology providers (field tests). The GSA conducts these field tests to identify pipeline pre-commercial solutions that hold promise for cost-effectively reducing energy consumption in buildings within the GSA portfolio. GPG hosts field tests in federal facilities and develops publicly available validation reports on the performance of the solutions. High-performing technologies are showcased and prioritized for wider deployment within the federal portfolio, thus driving down utility expenditures in the federal sector. Outcomes of field tests inform BTO component-level and integration research and development priorities. Key field test considerations include the complexity of integration, time, cost, and the disruption associated with the measure. CBI is also developing a framework to capture and share field test data for grid-responsiveness research, utility program development and to improve assumptions included physics-based building models.

4 Analysis – LED Troffers and Controls

4.1 Evaluation of Current Market Landscape

4.1.1 Key Sectors and Applications

LED troffers and controls have applications in all sectors of commercial buildings and provide opportunities for significant energy savings. Lighting accounts for approximately 15 – 20% of commercial building energy consumption. Most commercial buildings use linear fluorescent lighting fixtures; in 2012, fluorescent lighting systems accounted for more than 75% of commercial building lighting by floor space.[6] The most common commercial lighting fixtures are: 2' x 4', 2' x 2', and 1' x 4' recessed lighting troffers. LED troffer technologies have the potential to provide up to 40-70% energy savings in typical commercial office building applications. Energy savings can reach up to 80% if lighting control systems (e.g., motion sensors, daylighting sensors) are incorporated. Savings associated with lighting controls can be particularly high in intermittently occupied spaces.[7,8]

A broad range of LED troffer and control technologies are available for both new construction and retrofit applications. There are varying degrees of retrofit options for installing LED technologies in existing buildings, including replacing the lamp with an LED lamp, replacing the lamp and other luminaire components with an LED retrofit kit, or replacing the entire luminaire with a luminaire designed for LED lamps, including integrated control sensors. Although adoption of LED troffers has been increasing steadily, Figure 2 shows that LED technology still represents less than 2% of current installed base of linear fixtures in commercial buildings.[9]

[6] EIA. 2017. "Trends in Lighting in Commercial Buildings." Commercial Buildings Energy Consumption Survey (CBECS) 2012. May 17, 2017. Available at: https://www.eia.gov/consumption/commercial/reports/2012/lighting/?src=%E2%80%B9%20Consumption%20%20%20Commercial%20Buildings%20Energy%20Consumption%20Survey%20(CBECS)-b1; Also cited in Solid-State Lighting Technology Fact Sheet, DOE BTO. January 2017. Available at: https://www1.eere.energy.gov/buildings/publications/pdfs/ssl/led_troffer-upgrades_fs.pdf

[7] A 2015 compilation of data from 16 lighting control demonstration sites showed an average use reduction across all sites of 46%. Available http://www.gsa.gov/portal/content/240287

[8] LED Lighting - The New Low-hanging Fruit in a Lighting (R)evolution, Kyle Hemmi, CLEAResult.

[9] BBA High-Efficiency Troffer Lighting Specification Brochure, DOE BBA, Available at: https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/BBA_Troffer_Fact_Sheet_vf_0.pdf

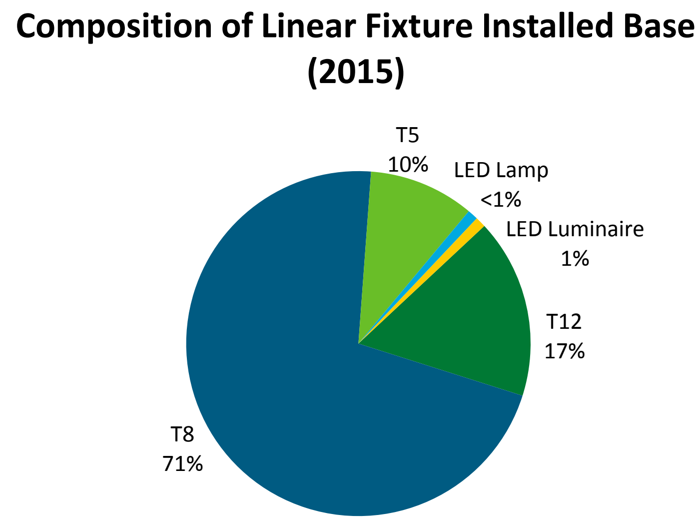

Figure 2: Composition of linear fixture installed base

Source: Navigant (2015)[10] Note: The 2015 Adoption report focused on many fixture types including linear fixtures (those that traditionally utilized a linear fluorescent lamp). Troffers would be included within this overall linear fixture category.

4.1.2 Major Manufacturers

The LED troffer and controls market consists of a range of different industry players, from large multinational corporations to small startup companies. Many of the larger players provide holistic lighting solutions including troffers, lamps, and controls for all the major lighting types; alternatively, many of the smaller companies focus only on specific technologies or products. Table 10 lists the major industry players in the LED lighting space and identifies each player's target market and sector.

Table 10: Major Industry Players - LED Troffers and Controls

Company	Products	Target Markets
GE Lighting	All major lamp and luminaire technologies	Global, large U.S. focus
Philips	All major lamp and luminaire technologies	Global
Acuity Brands Inc.	All major luminaire technologies	North America, some international
Eaton Lighting	All major luminaire technologies	Global, large U.S. focus
Cree, Inc.	LED lamps and luminaires	Global
Hubbell Lighting, Inc.	All major luminaire technologies	North America, some international
Lutron	Control technologies	Global
WattStopper	Control technologies	Global

[10] Navigant. 2015. "Adoption of Light-Emitting Diodes in Common Lighting Applications." July 2015. Prepared by Navigant for the U.S. Department of Energy SSL Program. Available http://energy.gov/sites/prod/files/2015/07/f24/led-adoption-report_2015.pdf.

4.1.3 Relevant CBI Work and Resources

CBI is working with the SSL Program within BTO's Emerging Technologies (ET) Group to better understand the benefits and energy savings associated with the integration of LED lighting and control technologies into commercial buildings. Current activities support a range of efforts, including research projects, laboratory testing, and field studies. Although BTO has supported many field tests of LED lighting technologies through its GATEWAY Program,[11] most of the these have focused on LED spot, exterior lighting, and other non-troffer LED types. The Federal Energy Management Program (FEMP) also supports development of resources to speed the adoption of troffer lighting and control systems in federal buildings. Table 11 summarizes some of the most relevant activities supported by CBI, FEMP, and the SSL team for LED troffers and controls.

Table 11. Related DOE Troffers and Controls Activities

Project Title	Lead Performer	Report Link
CALiPER Snapshot: TLEDs [tubular or troffer LEDs]	Pacific Northwest National Laboratory (PNNL)	Link
LED Retrofit Kits, TLEDs, and Lighting Controls: An Application Guide	PNNL	Link
2016 ILC Exemplary Performance Case Studies	PNNL	Link
Wireless Occupancy Sensors for Lighting Controls: An Applications Guide for Federal Facility Managers	PNNL	Link
Market research on the adoption of SSL and future savings potential	Navigant Consulting	Link
CALiPER Snapshot: Troffers	PNNL	Link
Evaluation of an LED Retrofit Project at Princeton University's Carl Icahn Laboratory	PNNL	Link
CALiPER Report 21.4: Summary of Linear (T8) LED Lamp Testing	PNNL	Link
Exploratory Study: Recessed Troffer Lighting	PNNL	Link
LED T8 Replacement Products: Seattle, Washington	PNNL	Link
Electronics, Lighting, and Networks Group (focusing on lighting controls, communications networks, and electronics)	Lawrence Berkeley National Laboratory (LBNL)	Link
Measured Energy Savings from Lighting Controls at 16 Demonstration Sites	LBNL	Link
LED Office Lighting and Advanced Lighting Control System	Pacific Gas & Electric (PG&E)	Link
Study on Luminaire Level Lighting Controls	Northwest Energy Efficiency Alliance (NEEA)	Link
A Meta-Analysis of Energy Savings from Lighting Controls in Commercial Buildings	LBNL	Link

Source: Developed by Navigant research and DOE national laboratory subject matter experts.

DOE also supports private sector engagement through the Better Buildings Alliance (BBA), DOE's partnership program with key industry players focused on improving the energy efficiency of commercial buildings. The BBA High-Efficiency Troffer Performance Specification provides a framework for commercial building owners on best practices for selecting and installing LED lighting systems. Since 2012, the BBA has maintained a High-Efficiency Troffer Lighting Specification, which offers suggested optimal performance

[11] http://energy.gov/eere/ssl/gateway-demonstrations

requirements for high-efficiency LED and fluorescent troffer products in the 2' x 4', 2' x 2', and 1' x 4' configurations. An updated version of the specification was released in January 2017 (version 6.0).[12]

4.1.4 Barriers

LED troffer and control technologies have developed into highly advanced lighting solutions; however, they still face significant barriers to adoption. Opportunities to improve this technology, as they are known to DOE, are detailed in Table 12.

Table 12. Barriers – LED Troffers and Controls

ID	Barrier	Description
1	Concerns over product inconsistency	Perceptions of quality and performance inconsistency among LED products has led to skepticism and uncertainty by commercial building owners, making them less likely to install LED technologies. Even with recent product improvements, anecdotal concerns may remain. Because of these inconsistencies, buyers need to spend more time evaluating products, especially when making large purchases. This adds cost and increases risk.
2	Performance inconsistency	The performance of some LED products changes based on operating time and environmental conditions, such as ambient temperature. This can lead to potential problems with color consistency, flicker, and glare. These issues present barriers to adoption by commercial building owners, particularly in applications that require high-quality, consistent lighting.
3	Controllability	The primary technical barriers in LED lighting controls include improving the quality of LED dimming controls and developing more standardized design and control strategies to increase integration of LED lighting and control technologies with other building and energy management technologies. Additionally, compatibility between hardware and software systems is a limiting factor. Most building owners have stated that the lack of interoperability between building systems has hindered building performance evaluation, thus leaving owners without a full picture of building operations. Data should be exchangeable between systems (e.g., fixture status, occupancy, energy consumption).
4	Lack of data on daylighting control performance	There is insufficient data on how reliably fixtures with individual or autonomous controls perform. Recent LED demonstrations have evaluated total energy performance, but few, if any, have evaluated if historical issues related to daylighting (such as hysteresis and inappropriate dimming on a per fixture or zone basis) have been solved with these new products.
5	Upfront cost	Although the costs of LED technologies have dropped significantly and continue to decline, one of the single largest barriers to the adoption of LED troffers is their high upfront cost relative to legacy lighting technologies. Despite the proven short-term payback period of LEDs in some applications, the payback may still not be immediate enough for some commercial building owners. Fluorescent systems are efficient, and the actual energy cost of operating a troffer equates to $18–$53 annually, with a typical operating cost of around $28 of energy per year. The cost of a new luminaire along with labor to install is hard to offset when the annual unit costs of the troffers is so low. A 50% energy translates to around $15 – which means that to achieve even a 5-year simple payback that the equipment and labor must only cost $75.

[12] BBA High Efficiency Troffer Specification. Version: 6.0. January 2017. https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/BBA_High_Efficacy_Troffer_Specification_V6_vf_1.pdf

ID	Barrier	Description
7	Lack of compatibility and interoperability	LED lighting retrofit technologies are available for most applications. However, current lighting infrastructure and a lack of interchangeability in some applications still limit opportunities for LED adoption. Greater interoperability of lighting control components and more universal specifications for lighting control systems are required to maximize the energy savings potential from LED troffers and controls.
8	Security concerns	LED troffers with controls can be tied directly into building data networks to enable communication between the troffers themselves, as well as with other lighting and building systems controls. The addition of these extra devices to the network brings with it concerns over potential network security issues or the creation of unintended access points.

Sources: Table developed by Navigant and DOE national laboratories, and fall 2015 stakeholder workshop participants.

4.1.5 Other Complementary Programs and Cross-Cutting Opportunities

In addition to CBI's efforts, many energy efficiency organizations also play important roles in LED technologies transformation. Table 13 summarizes some programs and activities that other government and non-government organizations have conducted.

Table 13. Other Efforts Supporting Adoption of LED Troffers and Controls

Provider	Program Highlights	Source
GSA GPG	Has conducted preliminary or real-world technology assessments in: • LED replacement lamps for compact fluorescent lamps • LED retrofits for fluorescent luminaires • Networked lighting • LED lighting with integrated controls • LED retrofit luminaires • Wireless lighting control system	Link Link
Federal Energy Management Program (FEMP)	• Provides guidance for commercial and industrial luminaires, including troffers, which are a covered category within the FEMP efficiency requirements. • Deploys technology efforts including wireless lighting occupancy sensors, which have been designated as a "promising technology" for potential future focus.	Link Link
Design Lights Consortium (DLC)	• Since 2010, administers the Qualified Products List, a leading resource that distinguishes quality, high-efficiency LED products for the commercial sector. • Released an updated Network Lighting Control Systems Specification V1.02 and report in 2017.	Link Link
New York State Energy Research and Development Authority (NYSERDA)	• Conducts SSL R&D and demonstration projects	Link
NEEP	• Works with market players throughout the SSL industry across North America and around the world to maximize the potential of LED technologies, including commercial lighting and controls	Link
NEEA	• Develops luminaire level lighting controls initiative	Link

Provider	Program Highlights	Source
Midwest Energy Efficiency Alliance	• Produces the Midwest Advanced Lighting Solutions Guide • Facilitates the Lighting Utility Midwest Exchange Network (Midwest LUMEN)	Link
PG&E	• Develops emerging technology projects including retrofits for LED troffers with control systems in office space • Offers many rebates for LED lighting measures • Considers potential rebates for troffers in the future	Link

Source: Developed by Navigant, DOE national laboratory reviewers, and 2015 stakeholder workshop participants.

4.2 Technical Opportunities

In 2015, DOE outlined a joint SSL/CBI strategy for lighting controls. In 2017, the Design Lights Consortium completed a study on how data from lighting controls can improve energy savings estimates. In 2015, GSA's GPG program released the results of several lighting controls demonstrations that verify 20%–40% more energy savings than with a troffer retrofit alone. NEEP examined these issues in FY 2016 as part of the Advanced Lighting Controls demonstration program. Finally, NEEA is conducting assessments of luminaire level controls to identify the granularity necessary to balance energy savings with cost of lighting control systems.

Thus, much foundational work has examined the energy savings opportunity for LED controls. However, significantly less research touches on which controls strategies can cost-effectively multiply energy savings and/or what additional benefits such as HVAC system energy savings and/or grid responsiveness, can be achieved with luminaire-based controls. Preliminary investigation on the capabilities of current sensors and connectivity modules and how they are currently installed or included in lighting fixtures will enable a better understanding of functional capabilities, benefits, capability gaps, and integration opportunities for LED troffers and controls.

5 Analysis – Energy Management and Information Systems

5.1 Evaluation of Current Market Landscape

5.1.1 Key Sectors and Applications

Building controls, information, and management systems and related "smart building" technologies are evolving rapidly, driven by advancements in data collection, connectivity, and computing power. The scope of commercial building offerings in this space can be confusing and varied terminology is used throughout the industry and literature. Terms such as energy management system (EMS), energy information system (EIS), building management system (BMS), building automation system (BAS), and energy management information system (EMIS) are often used interchangeably, to describe the same or similar solutions.

In response to this complex and overlapping assortment of terminology and technologies, the DOE BBA Energy Management Information Systems Technology Research Team (EMIS Team) developed a consensus-driven technology classification framework.[13] Based on this framework, the working definition of an EMIS covers a broad family of tools and services used to manage and control commercial building energy use. This framing is used to understand principal design intent and core functionality, although certain commercial

[13] Granderson, J. 2013. "Energy Management and Information Systems (EMIS) Technology Classification Framework." LBNL. August 29 2013. http://eis.lbl.gov/pubs/emis-tech-class-framework.pdf

offerings may cross categories – for example, some EISs may offer FDD modules or benchmarking capabilities. In this document, the term EMIS refers collectively to these technologies.

CBI's HIT efforts focus primarily on EIS, HVAC optimization, and FDD technologies to identify low-cost/no-cost operational improvements to existing building systems and to conduct continuous monitoring, tracking, and commissioning. Other programs in the CBI portfolio focus more heavily on benchmarking and monthly data analysis tools.

An EMIS can be installed either during construction of a new building or as a retrofit measure in an existing building. In both applications, the goal is to save energy through continuous monitoring, diagnostics, and control of whole-building and/or system-level energy consumption and operations (e.g., HVAC; lighting; plug loads). EMISs are often used to:

- Identify operational efficiency opportunities (e.g., scheduling, faults, suboptimal control, excessive usage)
- Trend and compare building performance to historical data
- Benchmark energy use and operations against other similar buildings or like equipment
- Monitor and manage peak loads and demand charges
- Inform external data analytics services.

The energy savings that are enabled using EMISs depend on four key factors: (1) the specific type of EMIS used, (2) the energy consumption of the building prior to the installation of an EMIS, (3) the proper installation and commissioning of the EMIS, and (4) the extent to which the EMIS is well-integrated into organizational business processes. Case studies suggest that EMISs can enable site energy savings of up to 20%. A synthesized analysis of the use of analytics across two dozen organizations that was performed by the EMIS Team found median energy savings of 17% and 8% for individual buildings and portfolios, respectively.[14] Operational improvements such as those achieved through commissioning, can be supported by EMIS; commissioning has been documented to deliver median savings of 16% with a 1.1 year payback.[15]

Although EMIS capabilities are rapidly evolving, the market offers many mature EMISs that can be applied across most building types and systems. Table 14 shows current revenue estimates for energy management products in North America by customer type. Note that the figures included in this table correspond to a more general definition of energy management systems adopted by the study publisher; EMISs include but are not limited to the technologies included in this market study, and vice versa.

Table 14. Estimated Energy Management System Revenue by Customer Type, North America: 2015

Customer Type	Revenue ($ Millions)	Percent of Total Revenue
Enterprise/Office	$287.8	37%
Government/Defense	$87.3	11%
Retail	$147.0	19%
Hospitality	$54.9	7%
Healthcare	$41.3	5%
Education	$82.1	11%
Other*	$67.2	9%

[14] Granderson, J, Lin, G. 2016. Building energy information systems: synthesis of costs, savings, and best-practice uses. Energy Efficiency, published online 19 Feb, 2016, pp.1-16. Available online October 2016. https://eetd.lbl.gov/sites/all/files/1006431_0.pdf

[15] Mills, E. 2009. "Building Commissioning – A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions. July 21, 2009. Available at: http://cx.lbl.gov/documents/2009-assessment/lbnl-cx-cost-benefit.pdf

Customer Type	Revenue ($ Millions)	Percent of Total Revenue
Total	$767.5	100%

*Other: food service, warehouses, or customers that have more specialized needs
Source: Navigant Research. "Building Energy Management Systems." 2015.

5.1.2 Major Manufacturers

The EMIS market consists of an evolving list of vendors and service providers, many of which have emerged in recent years. While several large corporations offer EMIS products, the market also includes many smaller players. Table 15 illustrates example suppliers, highlighting the diversity and breadth of offerings in energy management technology in the commercial buildings sector of the EMIS market. Because this industry is rapidly evolving—with players undergoing mergers, acquisitions, rebranding, and other activities with regular frequency—the table is a snapshot of providers as of the date of publication of this report.

Table 15. System Providers – Building Energy Management and Information Systems

EMIS Tool	Data Scope / Interval	Primary Applications	Vendor Examples*
Benchmarking and Utility Bill Analysis	Whole Building / Monthly	Utility bill reconciliation, energy use and cost tracking	EPA Portfolio Manager, Metrix, EnergyCAP, Noesis, Energy Print, FirstView
EIS	Whole Building / Hourly to 15 minute	Data visualization and automated interval data analysis	Obvius building manager online, Lucid Building Dashboard, Noveda Energy Flow Monitor, NorthWrite Energy WorkSite, Pulse Energy, EnerNOC EfficiencySmart, Energy ICT EIServer, JCI Panoptix, EFT Energy Manager, Mach Energy Asset Manager, eSight Enterprise
BAS	Systems / 15 minute and less	System and equipment controls and alarms	Siemens Apogee, JCI Metasys, Novar Opus EMS, Tridium Niagara, Automated Logic WebControl
FDD	Systems / 15 minute and less	Automated identification of faults	Cimetrics InfoMetrics, EnerNOC EfficiencySmart, EZENICS, Sky Foundry SkySpark
Automated System Optimization	Systems / 15 minute and less	Automated modification of control parameters	Optimum Loop, Optimum VAV, BuildingIQ, Enerliance LOBOS, QCoefficient

*Note – representative examples, not intended to be a comprehensive inventory of market offerings.
Source: Granderson, J. 2013[16]

EMIS vendors offer an array of hardware, software, and services to their customers. Hardware can include sensors, controllers, wired (or wireless) devices, as well as public-facing user interfaces. Software may be installed locally, cloud-based, or app-based, which allows users to log in online from any Internet-enabled device. Additionally, many vendors, particularly those providing analytics or optimization solutions, offer their

[16] Granderson, J. 2013. "Energy Management and Information Systems (EMIS) Technology Classification Framework." LBNL. August 2013. Available at: http://eis.lbl.gov/pubs/emis-tech-class-framework.pdf

products through a software as a service model, which requires the customer to pay for an ongoing subscription to the vendor's software.

5.1.3 Relevant CBI Work and Resources

The EMIS Team focuses activities and industry engagement on commercial building EMIS. The EMIS Team has published performance support materials, market and field studies and application functionality overviews to better understand the operational efficiency gained through the effective use of EMIS. See Table 16 for a summary of EMIS research, projects, and other activities.

Table 16. DOE EMIS Research

Name	Lead Performer	Report Link
EMIS Overview, Business Case		
Energy Management Systems for Food Service Applications	BBA Food Service Team	Link
EIS Business Case Fact Sheet, Webinar presentation	LBNL/BBA EMIS Team	Link, Link
Costs and Energy Saving Benefits of EIS report	LBNL/BBA EMIS Team	Link
EMIS Technology		
Using EMIS to Identify Top Opportunities for Commercial Building Efficiency	LBNL/BBA EMIS Team	Link
EMIS Technology Classification Framework	LBNL/BBA EMIS Team	Link
Energy Information Handbook	LBNL/BBA EMIS Team	Link
Synthesis of EMIS Resources	LBNL/BBA EMIS Team	Link
EMIS Process, Implementation		
EMIS Specification and Procurement Support Materials	LBNL/BBA EMIS Team	Link
EMIS Organizational Primer	LBNL/BBA EMIS Team	Link
EMIS Crash Course	LBNL/BBA EMIS Team	Link
Regional Guide to EMIS Incentives	LBNL/BBA EMIS Team	Link

Sources: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

Table 17 summarizes CBI's EMIS-related projects or programs, while Table 18 summarizes BTO research and development in sensors and controls.

Table 17. DOE EMIS Projects

Title	Lead Performers	Overview	Report Link
Retro-commissioning sensor suitcase commercialization pilot project	PNNL, LBNL, Oak Ridge National Laboratory (ORNL)	Turnkey hardware and software solution that enables non-experts to automatically generate low- or no-cost efficiency and operational improvements.	Link
BuildingIQ Tech Demo	BuildingIQ Inc., Foster City, CA	Next generation of advanced building system optimization technology.	Link

Title	Lead Performers	Overview	Report Link
Smart Energy Analytics Campaign	LBNL/BBA EMIS Team	Encourages and tracks adoption of EMIS technology used with monitoring-based commissioning (MBCx) and other energy management processes	Link
Using EMIS for Savings Estimation	LBNL	Assessment of automated measurement and verification (M&V) methods for whole building energy efficiency using EMIS	Link
Envision Charlotte	UNC Charlotte, PNNL, others	3-year campaign to achieve 20% energy savings in Greater Charlotte region through smart city initiatives, including EMIS adoption	Link
Integrating Models for Better Building Efficiency	Lucid, LBNL	Integrating the Lucid platform with additional specialized analytics and databases from the National Labs will improve statistical modeling techniques used in building management software.	Link

Sources: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

Table 18. DOE Efforts Supporting Sensors, Controls, and Transactional Networks

Title	Lead Performers	Report Link
VOLTTRON	PNNL	Link
Building Energy Management Open-Source Software Development (BEMOSS)	Virginia Tech Advanced Research Institute	Link
Integrated Sensors and Controls	LBNL, U.S.-India Joint Center for Building Energy Research and Development (CBERD)	Link
Monitoring and Benchmarking for EIS	U.S.-India Joint CBERD	Link
Sensors, Controls, and Transactive Energy Research	PNNL	Link
University-Industry-National Laboratory Partnership to Improve Building Efficiency by Equipment Health Monitoring with Virtual Intelligent Sensing	ORNL	Link
Low-cost Wireless Sensors for Building Monitoring Applications	ORNL	Link
Building Re-tuning	PNNL	Link
Smart Buildings Equipment Initiative	PNNL, National Renewable Energy Laboratory (NREL)	Link
Transforming Ordinary Buildings into Smart Buildings via Low-Cost, Self-Powering Wireless Sensors and Sensor Networks	Case Western Reserve University, Cleveland, OH	Link

Sources: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

5.1.4 Barriers

While building sensing, communication, control, and automation technologies have evolved rapidly into robust and versatile energy management solutions, they are still significant opportunities for improved product development and delivery. Descriptions of the technical and market barriers are detailed in Table 19.

Table 19. Barriers – Energy Management and Information Systems

ID	Barrier	Description
1	Lack of compatibility and interoperability	Fragmentation of communication protocols, a lack of common naming conventions or standard methods for associating data points between EMIS, existing BAS, optimization algorithms, and existing building systems (e.g., non-BAS-controlled HVAC, lighting) makes it difficult to integrate multiple systems into centralized EMIS. The proliferation of gateways, closed (proprietary) communication protocols and systems prevents quick and inexpensive adoption of EMIS. This is exacerbated by the time and cost associated with these issues.
2	Challenge of retrofit installation	As for many building technologies, retrofitting buildings with requisite instrumentation for an EMIS is more difficult than outfitting them during new construction. While wireless systems may provide flexibility for some elements of building retrofits, wireless sensor technologies may pose security issues. Some building managers mistrust wireless systems in environments that require extremely high system reliability. Additionally, while perceived as more reliable, wired sensor installation is often cost-prohibitive in retrofit applications.
3	Transaction costs and value proposition	A lack of clarity within the industry regarding standard definitions and functionalities of EMIS makes procurement of EMIS platforms complex and time consuming. Limited information on and wide variability of applications makes it difficult for buyers to estimate the costs and benefits (e.g., energy, cost savings) of EMIS.
4	Difficulty of integration	Many commercial buildings already have some building automation features in place, and owners may wish to build on those rather than start anew with a completely different system. Often no one offering satisfies all requirements, and related to the interoperability issue, piecemeal integration of automation, control, information, and management systems can make linkages technically challenging, and thus very costly.
5	Scalability for smaller buildings	Costs are coming down and many solutions are cost-effective for large owners and enterprises, but a key barrier to adoption is that the systems are perceived as too expensive in smaller buildings and are not used at all. In small buildings, the dollar value of the energy savings that are enabled may not be high enough to offset the costs of ownership.
6	Organizational integration	EMIS-related energy savings can depend heavily on the ability to incorporate use of the EMIS into organizational practices. Since EMIS are a “human-in-the-loop” process tool, as opposed to high-efficiency equipment, it is necessary to train users, establish standard procedures to respond to insights gained through use of the tool, and allocate staff time and responsibilities for maximum technology benefit. Because each organization is unique, and because data-driven energy management is relatively new, this can be a challenge.

ID	Barrier	Description
7	Market and technical diversity	While technology options are generally a benefit, today's EMIS market abounds with different platforms and options for data analyses. Users are often left wondering what to do first, which data to analyze, and which points to meter.

Sources: Table developed by Navigant and DOE national laboratories, and 2015 stakeholder workshop participants.

5.1.5 Other Complimentary Programs and Cross-Cutting Opportunities

In addition to CBI's efforts, other organizations also support EMIS programs. For a comprehensive and interactive guide on EMIS incentives, refer to LBNL's database of EMIS and Energy Management Incentives,[17] which provides a state-by-state summary of utility and government incentive programs for various types of EMISs. In addition, Table 20 summarizes some of the programs and activities that other government and non-government organizations have conducted in support of EMIS.

Table 20. Other Programs Supporting Adoption of Energy Management and Information Systems

Provider	Program Highlights	Source
Consortium for Energy Efficiency (CEE) Utility Members	• Commercial Whole Building Performance Programs – focusing on continuous energy improvement and EMISs	Link (2012) Link (2016)
Institute for Market Transformation	• Collaborative and replicable resources for owners and tenants, include EMIS as an existing technology that can be leveraged	Link
NEEA	• Inventory of Commercial and Industrial EMIS for M&V Applications	Link
RMI	• The Portfolio Energy Optimization initiative is developing software tools working with owners and testing new technologies to increase the efficiency of operating buildings	Link
Retail Industry Leaders Association	• Retail energy leadership model including EMIS as a key element	Link
American Council for an Energy Efficient Economy (ACEEE)	• Secondary research on the use of smart technology to save energy in existing buildings	Link
Project Haystack	• Industry consortium addressing issues of data integration and EMIS interoperability by defining a common standard for the exchange of buildings data, including reference implementations that are freely available.	Link
NYSERDA	• Control and Building Automation Systems ○ Provides guidance to help commercial building owners make energy efficiency improvements that measurably reduce energy costs and improve return on investments • Real Time Energy Management (RTEM) ○ The program supports building owners and building management companies, and service providers who help them to select, install, and use appropriate RTEM systems	Link Link

Sources: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts. Market Transformation Goals and Timeframe

[17] Smart Energy Analytics Campaign. 2017. "EMIS and Energy Management Incentives." Accessed May 2017. Available at: https://smart-energy-analytics.org/utility-incentives

In spring 2016, CBI launched a program to study market and technical dynamics associated with the use of EMIS for monitoring-based commissioning in existing buildings. This program, the Smart Energy Analytics (SEA) Campaign,[18] focuses on the use of FDD, automated system optimization and meter analytics, combined with continuous energy management and monitoring-based commissioning processes in buildings 50,000 square feet or larger. As part of this EMIS-focused effort, CBI will track implementation and usage specifics in commercial buildings, including actions taken and the associated energy savings benefits. A smaller set of partners is anticipated to provide more detailed information on technology costs, and labor resources committed to technology use. Information collected over the course of the 4-year program will be used to conduct technical and economic analyses to further to facilitate EMIS improvements through research and development. Additional data collected through the SEA Campaign will support the development and launch of more consistent utility rebate program structure and offerings.

5.2 Technical Opportunities

Over the past years, CBI has supported several efforts to date focusing on EMIS and related technologies. These foundational activities have served as groundwork for the current Smart Energy Analytics Campaign. A few of these have included:

- Wireless sub-metering challenge
- Retro-commissioning sensor suitcase
- BBA EMIS procurement support materials and library of adoption resources
- FDD demonstrations
- Building re-tuning (both for BAS-controlled buildings and those without a BAS)

In addition, CBI is evaluating the effectiveness of an automated HVAC system optimization offering and published a snapshot overview of AFDD offerings.

Continued documentation on the rapidly changing EMIS landscape will support the identification of technical gaps and requirements and lay the groundwork for specific research and development needs. Laboratory and field testing will create data and information to validate integration improvements and opportunities in specific building applications.

[18] https://smart-energy-analytics.org/

6 Analysis – Attachments

6.1 Evaluation of Current Market Landscape

6.1.1 Key Sectors and Applications

Attachments consist of a wide range of interior and exterior products that provide shading, insulating, and/or daylight management functions to existing glazing and fenestration systems. They also improve occupant comfort and workplace conditions. Attachments can be specified in new construction, and often are added as a retrofit to address comfort, energy, and peak demand challenges in existing buildings, particularly with the increase in glass areas in many newer commercial buildings over the last two decades. Attachments provide cost-effective and versatile methods to modulate solar heat gains, and thus space conditioning load, while maintaining visible transmittance, minimizing glare, and controlling or modulating daylight, thereby enabling the reduction of electric lighting loads. Some attachments, such as insulating shades, shutters, and storm windows, also can reduce overall window U-factor, and some can mitigate infiltration loads. Attachments may be applied inside the building, between glazing layers, or outside of the building, and as well as to skylights and sloped glazing. They are applicable in all climates and orientations, and for virtually all commercial building types.

The attachment industry is well developed in Europe, with sales that approximate new window sales. While interior devices are commonly specified in the United States, they are rarely optimized. The field of external devices, which have tremendous potential, is largely unknown in this country. Manually operated interior attachments and fixed external devices dominate their respective markets and generally fail to capture the full savings potentials across weather conditions, and across daily and seasonal sun angles. Motorized and automated systems are now offered by virtually all manufacturers for both new and retrofit applications and are widely used in Europe. The penetration rates in the United States are small for a variety of reasons described below. The increased probability of achieving aggressive energy performance goals with properly designed, installed, and operated active, “smart” systems is a key market driver for the trend toward automation.

The increase in new attachments products and controls has outpaced the designer and owner’s ability to reliably optimize, specify, install, and control these new products. As a first step to providing accurate, objective performance data, the Attachments Energy Rating Council (AERC), a public interest partnership, was formed in 2015 with support from BTO and the attachments industry. AERC consists of a broad range of public and private stakeholder representatives. Supported through a 3-year startup phase by DOE, the AERC seeks to certify, standardize, and disseminate rating information pertaining to a suite of interior and exterior attachment technologies. Because these technologies come in a wide range of shapes, sizes, materials, and operating strategies, it can be challenging to design and deliver systems that meet performance expectations, not only for energy and peak demand, but for thermal and visual comfort, which are key market drivers. Attachment technologies can be statically installed in place, but most are designed and configured for either daily or seasonal adjustment or real-time dynamic control to meet changing needs for energy and comfort. Dynamic control can be provided manually by occupants or via motorized and automated sensors and controls. This is the area of increased industry innovation and product development over the last few years, and provides the potential for much larger and more reliable energy savings.

Window treatments, as window attachments are sometimes referred to, have been shown to reduce summertime solar heat gain up to 65% on south-facing windows, and up to 77% on west-facing windows.[19] Systems may be coplanar to the facade (e.g., Venetian blinds and roller shades), or can be projecting, such as

[19] Energy-Efficient Window Treatments, Department of Energy, Available at: http://energy.gov/energysaver/articles/energy-efficient-window-treatments

awnings, overhangs, and side fins. Operable systems can be manually operated by hand crank, or motorized and automated via multiple sensor input such as linkages to BASs and EMISs. Fixed horizontal overhangs and awnings block light from the high summer sun while admitting light from the lower winter sun, which can be beneficial for heating and lighting in colder climates, although glare must be managed.[20] Operable systems, depending on the level of sophistication, can be integrated with a central building-wide automation system to be operated automatically, or can have autonomous control at the zone or space level to provide the desired local functionality, usually with some provision for occupant override. Other benefits of the use of attachments include potential for HVAC system downsizing in new construction or in conjunction with planned upgrades or retrofits, enhancement of daylighting energy savings, and solar control if an appropriate system is selected. The February 2014 DOE BTO Windows and Building Envelope Research and Development Roadmap[21] estimates that inclusion of attachments in the U.S. commercial building stock has the potential to save 461 TBtu of primary energy annually.

Figure 3 illustrates the wide range of attachment options that are available for commercial buildings.

Figure 3. Examples of attachments
Various sources[22]

6.1.2 Major Manufacturers

The commercial building attachment industry is highly fragmented, with suppliers having varying levels of vertical integration and different distribution channels. Table 21 provides a snapshot of representative industry players. These range from suppliers that produce only components and materials (films, fabrics, motors, etc.), to vertically integrated firms that source their own materials, produce the attachments, utilize in-house distribution networks to route products to customers, include design services, and sometimes installation support and commissioning. Many of these products are either provided by local vendors (possibly part of a larger distribution network), are custom designed by an architect, or are provided by a construction materials supplier. The AERC will develop performance ratings including properties and annual energy impacts for interior and exterior attachment technologies.[23] The first rollout of the ratings for residential attachments will occur in FY 2017, to be followed by ratings for commercial attachments. However, the simulation and measurement methods and product databases that already have been developed by LBNL will be useable in the commercial sector before the final ratings are completed.

Table 21. Sample List of Industry Players – Attachments

Company	
Allied Window	MON-RAY
Ametco Manufacturing Corp.	Newell-Rubbermaid
Aristocrat Awnings	QMotion

[20] Reducing Supplemental Loads, ENERGY STAR, Available at: http://www.energystar.gov/ia/business/EPA_BUM_CH7_SupLoads.pdf
[21] Available at: http://energy.gov/sites/prod/files/2014/02/f8/BTO_windows_and_envelope_report_3.pdf
[22] From left to right: 1 and 2, http://www.wbdg.org/resources/suncontrol.php 3, http://zwhcherry916.en.ec21.com/Aluminium_Architectural_Vertical_Louver_for--5732818_5744867.html 4, http://www.homedesignfind.com/green/exterior-sun-shades-reduce-energy-use/
[23] http://aercnet.org/

Company	
Colt International	Renson
Construction Specialties	Rollac
Draper Inc.	Rollease-Acmeda
Glen Raven	Ruskin
Eastman Chemicol Company	Solar Shading Systems
Madico	Somfy
Hansen Architectural Systems	Spring Window Fashions
Hunter Douglas	Sun Control
Alcoa/Kawneer	Unicel Architectural
Lutron	Warema
MechoSystems	YKK Architectural Products

Sources: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

6.1.3 Relevant CBI Work and Resources

Recognizing the energy savings potential of attachments and the lack of consistency and standardization of attachments energy performance characterizations, DOE's Windows and Building Envelope R&D team, through a competitive solicitation, issued a request for proposals to select an organization to create a rating system. DOE selected a team assembled by the Window Covering Manufacturers Association (WCMA) to launch the AERC.[24] In 2015, the AERC established committees to develop a comprehensive rating system for interior and exterior fenestration attachments; and pathways to increase awareness, understanding, and adoption of attachments as an effective solar and shading management option to reduce building energy use and improve human comfort. To ensure that attachment ratings are based on accurate, objective data, the AERC will build its rating system on the Complex Glazing Database (CGDB) initiated by LBNL several years ago. It also follows the model of the International Glazing Database (IGDB) LBNL developed with NFRC and now contains data on more than 5,000 product listings. In 2016, LBNL will release two updates to the CGDB and expects more frequent releases in the future. The AERC will launch development of a certified product database that will store the final attachment energy ratings. The certified products database is expected to be completed in FY 2017 for selected classes of products. It will provide stakeholders, such as architects, energy modelers, manufacturers, code officials, and utility program managers, with credible, transparent, and actionable information to compare and select appropriate fenestration attachments for specific use cases. The AERC is initially focusing on development of ratings for residential products. The development of ratings for commercial building attachments will leverage many of the residential ratings.

Table 22 summarizes some of the relevant activities that BTO has supported for attachments in commercial buildings.

Table 22. DOE Attachments Projects

Provider	Program Highlights	Link
AERC	• Develops and promotes attachment ratings	Link
LBNL	• Advanced Windows Testbed: allows for side-by-side testing of window shading technologies and measurement of their effect on solar heat gain, daylight, and glare within a controlled office-like space. • FLEXLAB – allows for side-by-side outdoor testing of interactions of glazing and attachment configurations with lighting and HVAC at any building orientation, with office furniture and occupants if desired.	Link (Windows) Link (Facades)

[24] Attachments Energy Rating Council, - Available at: http://energy.gov/eere/buildings/downloads/attachments-energy-ratings-council

Provider	Program Highlights	Link
ORNL	• Flexible Research Platform – allows for testing of interactions of glazing and attachment configurations with HVAC systems at the whole building level with emulated occupancy.	Link
GSA GPG	• Conducts field tests of applied films and interior supplementary insulating glazing in GSA portfolio buildings.	Link
CBEI	• Organization to study and enable deep energy retrofits in small and medium-sized commercial buildings • Conducted market analysis of shading, films, and window attachments, providing recommendations for improving uptake of these technologies in the U.S. small- and medium-size commercial building market.	Link

Sources: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

6.1.4 Barriers

Shading and insulating attachments for commercial buildings are mature technologies, although they are still evolving. As previously noted, attachments are extensively used in the United States as interior systems, but have very limited use as exterior systems, even while they are ubiquitous in European markets, where there are more product options, greater experience in design and installation, and lower costs. Both technical and market barriers have inhibited widespread adoption in the United States. Table 23 provides an overview of the technical and market barriers.

Table 23. Barriers – Attachments

ID	Barrier	Description
1	Complexity of dynamic shading systems	Dynamic systems employ sophisticated sensors and control systems to automate operation. In the United States, a shift to more open, interoperable systems will have the largest long-term benefit on cost and reliability; in the short term, more training and education is needed to ease installation, reduce cost and complexity, and enable the adoption of existing lower cost motors, sensors, and controls.
2	Maintenance challenges	On large commercial buildings that require window cleaning, certain types of external shades could impede window cleaning operations. Additionally, some external shading types may invite nesting birds, which bring another set of maintenance issues. Attachments need to be designed and installed with building maintenance practices in mind.
3	Lack of accessible modeling tools and design information	Accessible, functional energy assessment tools are needed to guide decision-making and selection from among the wide variety of systems. Architects are often forced to rely on general guidelines to design expensive custom systems. Designers need assistance in quantifying the relationships among shading, HVAC, and lighting energy use, and between energy use and comfort to properly quantify energy saving, acceptance, and return on investment.
4	Difficulty with code applications and lack of voluntary programs	Building owners and architects have expressed concerns regarding the application of code requirements that may deter the use of attachments, especially projecting attachments. Furthermore, major categories of attachments products with differing energy savings potential and tradeoffs are sometimes lumped into the same code or program category. Code officials need data to support savings generated by the automated dynamic systems.

ID	Barrier	Description
5	Lack of energy impact awareness	Owners and designers need accessible and easy-to-understand information on the impact of solar heat gain to better quantify the cost-effective benefits of shading technologies. Window systems do not directly consume energy, so educating potential adopters on the synergies in energy savings possible through coordination of shading, lighting, and HVAC systems is critical to inform the business case for adopting the technology. Furthermore, comfort is a market driver that is understood by most owners and is getting increased attention with the growing emphasis on occupant well- being in voluntary programs like Leaders in Energy and Environmental Design (LEED). Owners and facility managers need best practices and guidance on long-term phased asset replacement or retrofit strategies based on appropriate timing and budgeting, including systems tradeoffs, O&M requirements, and energy savings potential.
6	Impact on aesthetic appeal and consumer acceptance	Most shading systems are designed to be aesthetically pleasing as well as functional, and blend in with the overall design of the building. However, building owners may not care for the look of shading devices, particularly on a building that has a distinctive style. Automation can enhance the appearance of the building if all the shades are deployed uniformly.
7	Lack of architect understanding and acceptance	Designers can incorporate attachment technologies most cost effectively during new construction or major retrofit periods, such as window replacements. Properly designed systems can allow resizing of HVAC ducts and chillers, and in some cases, can eliminate fan coil systems adjacent to the window. If shading systems are not sized and positioned correctly for a given building's location and orientation, then they will not function correctly. In all climates, proper design is critical to ensuring that shading devices produce performance characteristics that increase comfort and provide desired energy savings outcomes.
8	Lack of standardization	The lack of standardization in product sizes, materials, and mounting methods adds cost complexity and makes design difficult and time consuming. In addition, barrier is the lack of interoperability between controls for these systems and controls serving other building systems, such as lighting and space conditioning, increases cost, complexity, and risk.
9	Operation and occupant interaction	Most types of attachments may require some form of occupant operation or engagement. This is most commonly seen in the case of interior shading devices such as blinds, though it applies to some exterior technologies. In these instances, the level of engagement by occupants may be a barrier. Automation may improve these interface issues if executed properly, but requires adequate training of facility managers who may also need to override automation to address user specific needs. Devices may not be used for their optimal solar load mitigation because of the time and effort required to maintain automation along with occupant requirements.

Sources: Windows and Building Envelope Research and Development Roadmap, DOE BTO, http://energy.gov/sites/prod/files/2014/02/f8/BTO_windows_and_envelope_report_3.pdf;
Energy Efficient Building Envelopes Technology Roadmap, 2013, International Energy Agency, http://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergyEfficientBuildingEnvelopes.pdf;
CBEI: Shading, Films, and Window Attachments Market Report. http://energy.gov/eere/buildings/downloads/shading-films-and-window-attachments-market-report. Additional material developed by Navigant, DOE national laboratory reviewers, and stakeholder workshop participants.

6.1.5 Other Focus Programs and Cross-Cutting Opportunities

In addition to DOE's efforts, many other organizations are also playing important roles. Table 24 summarizes some of the programs and activities by other government and non-government organizations.

Table 24. Other Attachments Programs

Provider	Program Highlights	Source
Sacramento Municipal Utility District (SMUD)	Energy efficiency measure demonstrations for: • Interior and exterior shading devices and window films • Photo- or time-activated awnings • Permanent shading devices	Link
Electric & Gas Industries Association	GEOSmart Residential and Commercial Energy Program is a low interest loan for building upgrades, including window shading technologies	Link
Northwest Energy Efficiency Council	Solar Gain Management Fact Sheet, provides guidance on shading systems for mitigating solar heat gain within commercial buildings	Link
PG&E	Supporting field tests in LBNL FLEXLAB that include interior and exterior attachments	Link
European Solar Shading Organization	Develops guidelines, best practices, and ratings in Europe; many U.S. suppliers are global and members	Link
Purdue University	Facade Engineering Lab allows for testing of window shading technologies, including smart controls to operate shading attachments	Link

Sources: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

6.2 Technical Opportunities: Attachments

Voluntary rating programs, such as the U.S. Green Building Council (USGBC) Leadership in Energy and Environmental Design (LEED) and WELL Building Standard, incentivize early adopters to incorporate technologies into high-performance new construction. The AERC will provide consistent, accurate, and objective performance data to enable "apples to apples" design and purchasing comparisons of attachment systems. Members of the AERC will use standardized energy labels and messaging across the industry to capture attention from market leaders and early adopters in existing buildings.

Table 25. Key Attachments Envelope Partners

Key Attachments Partners	
American Architectural Manufacturers Association	American Institute of Architects
CEE	ACEEE
USGBC	IFMA
Fraunhofer	AERC
NEEA	WCMA

Source: Developed by Navigant based on DOE correspondence with partners and past activities.

Investigation with key stakeholders will document detailed technical and market application data and may uncover opportunities for additional product improvement for aesthetic qualities, integration with other building systems and comfort. Field tests would provide additional data to answer questions related to cost and energy performance.

7 Analysis – Cold-Climate Heat Pumps

7.1 Evaluation of Current Market Landscape

7.1.1 Key Sectors and Applications

In recent years, electric utilities in the northwest and northeast have heavily promoted cold-climate air-source heat pumps (CCHPs) in the residential sector. Technology enhancements allow residential CCHPs to achieve superior heating performance (both capacity and efficiency) at low outdoor temperatures, compared to conventional residential heat pumps. This makes them more energy-efficient than competing space-heating technologies at most outdoor temperatures. Similar technology enhancements, mainly variable-speed compressors and fans with overspeed compressor operation in heating mode, may also be applied to commercial unitary air-source heat pumps, allowing these products to offer similar energy-efficiency benefits.

Figure 4 shows that space heating represents 25% (1.7 quads) of commercial building primary energy consumption.

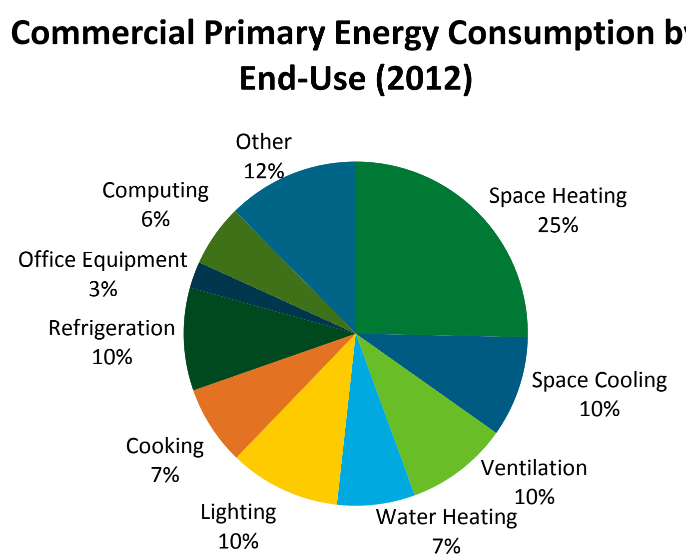

Figure 4. Commercial sector primary energy consumption

Source: EIA, 2012 Commercial Buildings Energy Consumption Survey: Energy Usage Summary, (March 18, 2016). Table E1. https://www.eia.gov/consumption/commercial/reports/2012/energyusage/

Using information from Scout, air-source heat pumps account for approximately 6% of commercial space heating primary energy consumption. (See Figure 5).

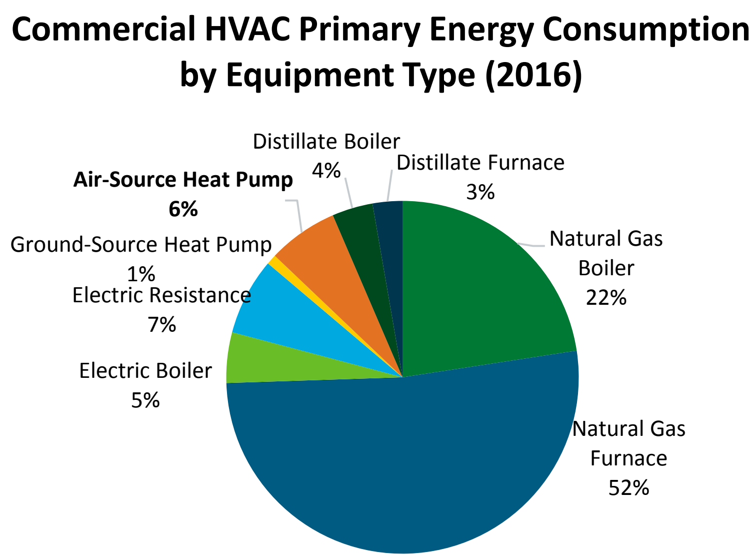

Figure 5: Commercial HVAC primary energy consumption by equipment type (2016)
Source: Scout tool for 2016

Three major types of commercial air-source heat pumps are available in the United States:

- Packaged rooftop heat pumps (see Figure 6)
- Split-system heat pumps (see Figure 7)
- Variable-refrigerant-flow (VRF) Heat Pumps (see Figure 8)

Packaged rooftop heat pumps currently dominate the market. VRFs are mainstream in major markets outside the United States, but have only a small share of the U.S. market, although their market share is growing quickly.[25] Split-system heat pumps are a relatively small player in the commercial market, mostly for smaller light-commercial applications.

Figure 6. Commercial packaged heat pumps
Source: 2015-06-09-10 Meeting Presentation: CUAC/CWAF ASRAC Working Group Fifth Meeting. https://www.regulations.gov/#!documentDetail;D=EERE-2013-BT-STD-0007-0091.

[25] http://www.achrnews.com/articles/131076-vrf-gaining-mass-appeal-in-the-us

Figure 7. Commercial split-system heat pump
Source: Carrier Commercial. http://www.carrier.com/commercial/en/us/products/split-systems/split-systems/.

Figure 8. VRF heat pumps
Source: Daikin VRV IV heat pump website. http://daikincomfort.com/products/vrvs/VRVIV-HeatPump.

Figure 9 shows that, in 2014, unitary heat-pump shipments were 11,258 units, or about 7% of the U.S. unitary air-conditioning market (these figures exclude VRFs).

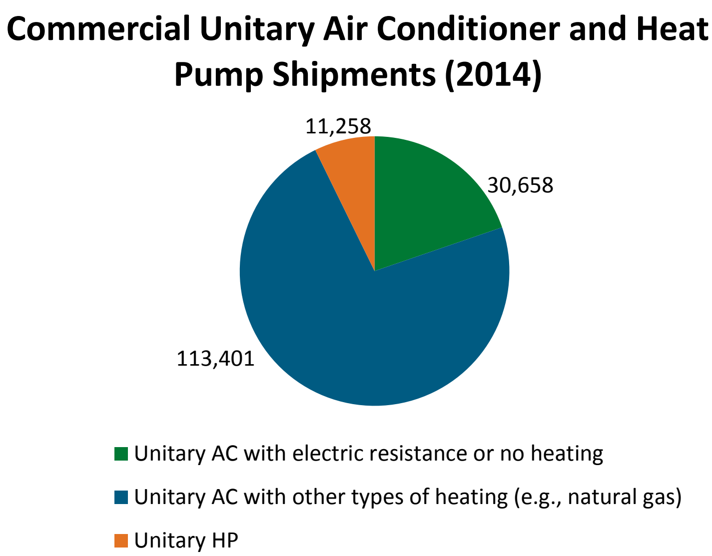

Figure 9. Commercial unitary air conditioner and heat pump shipments, 2014

Based on data from 7 of 9 major U.S. suppliers. Source: 2015-12 Direct Final Rule Technical Support Document: Energy Efficiency Program for Consumer Products and Commercial and Industrial Equipment: Small, Large, and Very Large Commercial Package Air Conditioning and Heating Equipment (2015), EERE-2013-BT-STD-0007-0105

7.1.2 Major Manufacturers

7.1.2.1 Unitary Packaged and Split-System Heat Pumps

Table 26 lists the major manufacturers of unitary heat pumps in the United States. Research found none that are specifically advertised as CCHPs. However, there is evidence that at least some of these products are likely to have good cold-climate performance. For example, a linear extrapolation of Air-Conditioning, Heating, and Refrigeration Institute (AHRI)-certified capacity and power ratings at the 47°F and 17°F outdoor-temperature rating points shows that 8% of listed products would have a coefficient of performance (COP) of at least 1.75 at 5°F outdoor temperature.

Achieving a COP of 1.75 or higher at 5°F is a common criterion for utility incentive programs for residential CCHPs (see Section 7.1.5), and thus it follows that this target would be of analogous interest in the commercial sector. Of these product lines, the Daikin Rebel series of packaged rooftop heat pumps employs variable-speed compressors (a feature of virtually all residential CCHPs) and claims heat-pump operation down to 2°F outdoor temperature (at ambient temperatures below this value, a backup form of heating packaged with the unit, such as gas or electric resistance heating, would be activated).[26] The Daikin Rebel RTU was the first to meet the DOE High Performance Rooftop Unit Challenge specification in May 2012[27] and participated in several case studies for the Advanced RTU Campaign.[28]

Another indicator of good cold-climate performance is the ratio of maximum heating capacity at 17°F and/or 5°F, if available, to rated cooling capacity. This ratio should be available for all commercial heat pumps for the 17°F rating point. Units with the higher ratios will provide better seasonal performance in cold climates compared to units with similar or moderately lower COPs at 17°F by reducing backup resistance heat use. Unitary units that have two-capacity or tandem compressors could provide higher ratios of maximum heating capacity at 17°F compared to the rated cooling capacity, if such units are configured to be operated and rated

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[26] http://lit.daikinapplied.com/bizlit/DocumentStorage/RooftopSystems/Brochures/ASP31-347_Rebel_Heat_Pump_Application_Brochure.pdf
[27] https://www1.eere.energy.gov/buildings/alliances/rooftop_specification.html
[28] http://www.advancedrtu.org/case-studies--guidance.html

in cooling mode only at the lower capacity stage. Tandem units have more potential in this regard than single two-capacity compressors due to the wider capacity difference and better low ambient performance. Such units could provide low ambient capacity ratios and COPs similar to oversped variable-speed units at lower cost. However, there appear to be no commercial CCHP product offerings of this type now.

Table 26. Major Industry Players – Commercial Unitary Heat Pumps

Company	Heat Pump Product Offering
Aaon	Packaged and Split
Lennox	Packaged and Split
Carrier	Packaged and Split
Daikin	Packaged and Split
Goodman (member of Daikin group)	Packaged
Johnson Controls	Packaged and Split
Nortek	Packaged
Rheem	Packaged and Split
Trane	Packaged and Split

Source: Table developed by Navigant and DOE national laboratory subject matter experts.

United Technologies Research Center (UTRC) has been developing a CCHP RTU since 2013 under the support of the BTO ET program.[29] The project has performance goals of 2.5 COP at -13ºF with < 15% capacity degradation for the 10-ton prototype. Laboratory testing shows current COPs of 1.8 for -13ºF, 2.7 for 17ºF, and 3.9 for 47ºF, which suggests that the full product would likely exceed the 1.75 COP at 5º threshold for CCHP performance.[29] The UTRC team is now working with Carrier to potentially commercialize the product, and also plans to begin a field study with the U.S. Department of Defense's (DOD) Environmental Security Technology Certification Program (ESTCP) program in 2018.[30]

7.1.2.2 VRF Heat Pumps

Table 27 lists the major manufacturers of VRF heat pumps sold in the United States. There is evidence that many of these products are likely to have good cold-climate performance. Manufacturers list minimum operating temperatures ranging from -4°F to -13°F, although at least some of these temperature limits are based on wet-bulb temperature rather than dry-bulb temperature. A linear extrapolation of AHRI-certified capacity and power ratings at the 47°F and 17°F outdoor-temperature rating points shows that close to 80% of listed products would have a COP of at least 1.75 at 5°F outdoor temperature.[31]

Table 27. Major Industry Players – Commercial VRF Heat Pumps

Company	Heating-Mode Minimum Operating Temperature (°F) *
Daikin	-13 (wet bulb)

[29] https://energy.gov/sites/prod/files/2016/04/f30/312104_Mahmoud_040716-945.pdf
[30] https://www.serdp-estcp.org/Program-Areas/Energy-and-Water/Energy/Conservation-and-Efficiency/EW-201721
[31] Most or all VRF products use variable-speed compressors. Extrapolating performance for variable-speed products introduces many uncertainties. However, given that a large percentage of the extrapolations suggest good cold-temperature performance, it's likely that many of these products can actually achieve good cold-temperature performance.

Company	Heating-Mode Minimum Operating Temperature (°F) *
Fujitsu	-4
GD Midea	-4
Gree	-4
Johnson Controls	-4
Lennox	-13
LG Electronics	-13 (wet bulb)
Mitsubishi	-13
Panasonic	-4
Toshiba Carrier	-5
Trane	-13
Samsung	-13

* Based on manufacturer published product literature. Unless indicated otherwise, the manufacturer did not specify whether the minimum operating temperature is dry-bulb or wet-bulb.

Navigant research found no VRF products offered in the United States that are specifically marketed as CCHPs. However, on its global product website, one manufacturer advertises an outdoor unit for low outdoor temperature use that uses two-stage compression technology to improve performance at low outdoor temperatures—as low as –13°F.[32]

7.1.3 Relevant CBI Work and Resources

Table 28 lists five DOE CCHP programs (both commercial and residential). Using one project as an example, the high-efficiency commercial CCHP, United Technologies Research Center demonstrated through laboratory testing that this packaged rooftop heat pump can achieve a 1.8 COP at -13°F with a capacity that is within 15% of the capacity at the 47°F rating point.[33]

Table 28. DOE Commercial and Residential CCHP Projects

Project Title	Target Market	Report Link
High-Efficiency Commercial CCHP	Commercial	Link
Natural Refrigerant High-Performance Heat Pump for Commercial Applications	Commercial and Industrial	Link
Split-System CCHP	Residential	Link
Low-Cost Gas Heat Pump for Building Space Heating	Residential and Commercial	Link
The Natural Gas Heat Pump and Air Conditioner	Residential and Commercial	Link

Source: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

32 http://www.daikin.com/products/ac/lineup/vrv/

33 As presented at the 2016 DOE BTO Peer Review: http://energy.gov/eere/buildings/downloads/high-performance-commercial-cold-climate-heat-pump

7.1.4 Barriers

Table 29 lists the key technical and market barriers to integration of commercial CCHPs in commercial buildings.

Table 29: Barriers – CCHPs

ID	Barrier	Description
1	Capital Cost Premiums	CCHPs can have a substantial first-cost premium compared to conventional heat pumps. VRFs, which tend to have superior cold-climate performance compared to conventional packaged or unitary split-system heat pumps, are significantly more expensive than these conventional products.
2	Purchaser First-Cost Sensitivity	Exacerbating Barrier 1 above, packaged RTUs, which represent the bulk of the unitary heat-pump market, tend to be used in applications where low first costs are of paramount importance to the purchaser (such as emergency replacement).
3	Retrofit Challenges	VRFs can be difficult and expensive to install in retrofit situations where conventional unitary equipment was originally installed. This may indicate a market need for low-cost ducted CCHP solutions.
4	Limited Documentation of Cold-Climate Performance	Manufacturers are not required to rate heat pumps at temperatures below 17 °F, and very few publish detailed performance information at colder temperatures. Demonstrations completed for small commercial and/or residential applications has produced inconsistent data.
5	Limited Product Offerings	Based on available performance data, less than 10% of packaged rooftop heat pumps, which represent the bulk of the unitary heat-pump market, are likely to achieve good cold-climate performance
6	Fuel Switching	Because buildings in colder climates commonly use natural gas heating, local utilities offering natural gas may be reticent to support a product that could potentially offset direct natural gas use for electricity. Even though CCHPs are intended for buildings that would otherwise use electric resistance heating, the perception of fuel switching may decrease the chance for energy efficiency program support. In addition, gas engine-driven or gas-fired absorption heat pumps with CCHP performance would likely not be supported by electric utilities as part of their CCHP programs due to fuel switching from electric heating to gas.

Sources: Table developed by Navigant and DOE national laboratories, and fall 2015 workshops stakeholder participants.

On the positive side, CCHPs generally offer superior comfort and indoor-air-quality benefits compared to conventional heat pumps. The variable-capacity capabilities of CCHPs allow them to maintain very uniform indoor air temperature and humidity year-round compared to conventional products. This can be a significant non-energy benefit in some applications.

7.1.5 Other Focus Programs and Cross-Cutting Opportunities

Table 30 lists examples of non-DOE residential CCHP programs. Research was unable to identify any current, non-DOE commercial CCHP programs.

Table 30: Other CCHP Efforts in the Residential Sector

Provider	Program Highlights	Source
NEEP	• Focuses on residential single-zone and multi-zone air source heat pump units. • Requires COP ≥1.75 at 5°F ambient.	Link
Massachusetts Clean Energy Center	• Rebate for residential single head and central/multi-head heat pump systems • Requires COP ≥1.75 at 5°F ambient. • Requires system deliver 100% of rated 47°F or 17°F capacity at 5°F	Link

Source: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

7.2 Technical Opportunities: CCHPs

DoD ESTCP field test data will show whether additional component or system-level integration work is required for CCHPs. Additional market and technical investigation will create a better understanding of the existing installed base, definitional needs, and factors impacting integration (workforce/training, installation and commissioning, product lead time and/or availability, operation, and warranty). Current research shows the lack of consistent definitions for CCHP, and thus a lack of manufacturer research and/or representation of units. A framework of cold climate heat pump performance definitions may shed light on the need for additional CCHP research and/or unit availability.

8 Analysis – Automated Fault Detection and Diagnostic Systems for Rooftop Units and Air Handlers

8.1 Evaluation of Current Market Landscape

8.1.1 Key Sectors and Applications

Satisfying the comfort and air quality demands while minimizing energy consumption in commercial buildings requires the precise interaction HVAC system components. HVAC systems must function in several operating modes and use numerous sensors and controls to coordinate the actions of different heating and cooling subsystems and their various moving parts (e.g., fans, motors, and dampers). Whether as a standalone packaged RTU or part of a larger distributed system using AHUs, the performance of HVAC systems often deviates from design or desired performance due to system malfunctions, equipment wear, manual controls overrides, and other causes. These faults often begin with little or no noticeable change in system performance or operation, but over time can lead to decreased capacity, efficiency, comfort, reliability, and longevity.[34] Semi-annual maintenance inspections often fail to identify faults due to the limited time the technician can observe the system and test individual components.

Table 31 and Table 32 highlight the potential efficiency degradation of RTUs caused by common system faults, such as low refrigerant charge and condenser or evaporator airflow reduction. While individual faults can cause moderate performance and efficiency decreases, the presence of multiple faults can have a substantial impact even for small fault levels. As Table 32 shows, even a collection of relatively small faults can reduce RTU efficiency by 15%, and several moderately severe faults reduce efficiency by 26%.

[34] See for example, the ACEEE report outlining common economizer faults and prevalence at http://aceee.org/files/proceedings/2014/data/papers/3-1007.pdf

Table 31. Example Performance Degradation from Common Single-Faults for RTUs

Fault Type	Fault Levels	Energy Efficiency Ratio (EER) Degradation	Notes
Low Refrigerant Charge	Low: -10% Med: -20% High: -30%	Low: +2% Med: -3% High: -25%	Slight EER increase based on relative drop in cooling capacity and electrical consumption
Condenser Airflow Reduction	Low: -16% Med: -37% High: -58%	Low: -17% Med: -24% High: -36%	Air-side EER
Evaporator Airflow Reduction	Low: -23% Med: -46% High: -67%	Low: -2% Med: -10% High: -23%	Air-side EER

Source: Southern California Edison. "Evaluating the Effects of Common Faults on a Commercial Packaged Rooftop Unit." ET13SCE7050. July 2015. http://www.etcc-ca.com/reports/evaluating-effects-common-faults-commercial-packaged-rooftop-unit?dl=1461105088.

Table 32. Example Performance Degradation from Common Multiple-Faults for RTUs

Fault Levels	Low Refrigerant Charge	Condenser Airflow Reduction	Evaporator Airflow Reduction	EER Degradation
Low	-10%	-17%	-23%	-15%
Medium	-23%	-37%	-46%	-26%
High	-30%	-58%	-67%	-52%

Source: Southern California Edison. "Evaluating the Effects of Common Faults on a Commercial Packaged Rooftop Unit." ET13SCE7050. July 2015. http://www.etcc-ca.com/reports/evaluating-effects-common-faults-commercial-packaged-rooftop-unit?dl=1461.105088.

To address this issue, manufacturers, service providers, and researchers have developed AFDD systems to provide greater insight into RTU and AHU operations and improve maintenance practices. AFDD systems consist of a suite of sensors, communication systems, and analytical algorithms that perform the following functions:

- Monitor various performance indicators
- Benchmark performance over time
- Detect when performance changes, indicating a fault
- Alert building staff when indicators suggest a fault
- In some cases, provide building staff with likely causes for the fault so that they can be readily addressed through maintenance and repair

AFDD systems provide energy savings and other comfort and operational benefits by increasing the likelihood and restorative impact of system maintenance. AFDD systems can quickly alert building staff or service technicians when a fault occurs, sometimes quantify the fault priority, impact, and/or savings opportunity, and then direct technicians to likely problem areas so that issues can be inspected and repaired rapidly. This reduces the amount of time the RTU or AHU operates below optimum efficiency and performance, and could provide up to 30% energy savings compared to common seasonal or annual maintenance practices.[35] In

[35] Energy savings estimates from research reports and vendor literature captured in Katipamula et al. 2016. "Sensors & Advanced Building Controls Project: Task 2: Develop, Test, and Validate Diagnostic and Self-Aware Concepts for Small Commercial Buildings." Presentation to DOE/BTO. February 10, 2016.

addition, AFDD systems could reduce maintenance and repair costs by catching small issues before they cause catastrophic damage over time. Some AFDD systems even can verify that the repairs and maintenance solved the issue and returned performance.[36] The non-energy benefits of AFDD, including building comfort and increased equipment reliability, are particularly valuable in applications where minimization of downtime is essential.

AFDD systems must balance the number of monitoring points, sensor types, diagnostic capabilities, sensitivity, accuracy, and other attributes with the product cost and installation complexity to ultimately meet the needs of the building staff. For this reason, AFDD systems for smaller buildings using RTUs commonly have fewer sensors than those for larger buildings with distributed and built-up AHUs and duct systems. Table 35 in Section 8.1.2 compares the features of several AFDD systems on the market today. More building codes and standards organizations, such as ASHRAE 90.1-2016 and International Green Construction Code-2015 (IgCC), recognize the value of AFDD systems. For example, AFDD requirements for California Title 24 Building Energy Efficiency Standard[37] highlights the capabilities of many systems:

- Temperature sensors to monitor: outside air, supply air, return air
- Operational status for economizers, cooling system, heating system, mixed air system.
- The FDD system shall detect the following faults:
    - Air temperature sensor failure/fault;
    - Not economizing when it should;
    - Economizing when it should not;
    - Damper not modulating; and
    - Excess outdoor air.

AFDD systems are available for both new and existing HVAC equipment. The California Building Code requirements apply to new RTUs with cooling capacities greater than 4.5 tons, and manufacturers have incorporated these AFDD capabilities into their products. Additionally, many vendors and researchers have developed retrofit AFDD systems that can integrate with existing RTUs and AHUs. Section 8.1.2 discusses various AFDD vendors and offerings in greater detail.

The market for AFDD systems will continue to grow as more manufacturers introduce products that provide onboard AFDD capabilities and as vendors increasingly offer retrofit AFDD analytics. Table 33 provides key information on HVAC energy consumption for small, medium, and large buildings and projects the potential savings from adding AFDD systems to all commercial building HVAC systems. Smaller buildings are primarily served by RTUs, large buildings by distributed systems with AHUs, and medium-size buildings with a mix of these technologies. Combined, these building types can potentially save 500 to 1,000 TBtu of site energy savings by using HVAC AFDD.

Table 33. HVAC Consumption in U.S. Commercial Building Stock

Characteristics	Small Buildings	Medium Buildings	Large Buildings	Total
Floor space Range (thousand sq. ft.)	≤ 50	>50 and ≤ 100	>100	–
Number of Buildings (thousands)	4,604	147	108	4,859

[36] Katipamula et al. 2016. "Sensors & Advanced Building Controls Project: Task 2: Develop, Test, and Validate Diagnostic and Self-Aware Concepts for Small Commercial Buildings." Presentation to DOE/BTO. February 10, 2016.
[37] California Energy Commission. 2015. "Building Energy Efficiency Standards for Residential and Nonresidential Buildings for the 2016 Building Energy Efficiency Standards." Title 24, Part 6, and Associated Administrative Regulations in Part 1. CEC-400-2015-037-CMF June 2015. Available at: http://www.energy.ca.gov/2015publications/CEC-400-2015-037/CEC-400-2015-037-CMF.pdf

Characteristics	Small Buildings	Medium Buildings	Large Buildings	Total
Total Floor space (billion sq. ft.)	36	10	25	71
Total Site Energy Consumption (TBtu)	2,889	913	2,722	6,524
Total Expenditures ($B)	51	15	42	108

Source: Katipamula et al. 2016. "Sensors & Advanced Building Controls Project: Task 2: Develop, Test, and Validate Diagnostic and Self-Aware Concepts for Small Commercial Buildings." Presentation to DOE/BTO. February 10, 2016.

As discussed previously, installation cost and complexity is a key consideration for the value proposition of AFDD systems. Several recent technology and market trends have helped improve the capabilities and reduce the upfront cost of installing and configuring AFDD systems, including:[38]

- Open-source standards for building and HVAC control systems (e.g., BACnet) allow for easier integration and communication than previous proprietary systems (though issues remain with proprietary implementations of open-source standards)
- Communication and information technology (IT) costs have decreased substantially in recent years
- Title 24 requirements for RTUs (greater than 4.5 tons in capacity) obligated manufacturers to respond to major market mandates, reducing the incremental cost.
- Research into low-cost sensors, advanced communication platforms, and analytic software, has a compounding effect of reducing the size, cost, and complexity of AFDD installations.

8.1.2 Major Manufacturers

Table 34 highlights the variety of manufacturers, service providers, and researchers that have developed AFDD systems for RTUs and AHUs. Most systems are designed as add-ons or retrofits to existing building systems, but many RTU manufacturers now offer at least some factory-installed AFDD capabilities in their products to comply with California Title 24-2016 standards. Many standalone FDD products are available for RTUs, whereas FDD capabilities for AHUs are available as part of larger, whole building FDD systems.

Table 34. Example System Providers – AFDD Systems for RTUs and AHUs

Company	Product / Service	RTU Capabilities	AHU Capabilities
Many RTU manufacturers	On-board AFDD systems	✓	
Belimo	ZIP Economizer	✓	
Field Diagnostics Inc.	FDSI Insight / Sentinel	✓	
ClimaCheck	ClimaCheck	✓	
Transformative Wave	Catalyst eIQ	✓	
Virtjoule	Virtjoule	✓	
Facility Dynamics	PACRAT		✓
UCtriX	DABO		✓
Cimetrics	Analytika		✓

[38] Katipamula et al. 2016. "Sensors & Advanced Building Controls Project: Task 2: Develop, Test, and Validate Diagnostic and Self-Aware Concepts for Small Commercial Buildings." Presentation to DOE/BTO. February 10, 2016.

Company	Product / Service	RTU Capabilities	AHU Capabilities
Iconics	Energy Analytix		✓
Johnson Controls	Metasys Enterprise		✓
McKinstry	EEM Suite		✓
Ezenics	Optimized Operational Readiness	✓	✓
CopperTree	Kaizen	✓	✓
SkyFoundry	SkySpark	✓	✓
KGS	Clockworks	✓	✓

✓ denotes the vendor markets capabilities for RTUs and/or AHUs, actual product capabilities may vary
Sources: Katipamula et al. 2016. "Sensors & Advanced Building Controls Project: Task 2: Develop, Test, and Validate Diagnostic and Self-Aware Concepts for Small Commercial Buildings." Presentation to DOE/BTO. February 10, 2016; New Buildings Institute. 2013. "Rooftop Units Fault Detection and Diagnostics – Part of the Evidence-based Design and Operations PIER Program." Prepared for California Energy Commission. March 2013. Available at: https://newbuildings.org/wp-content/uploads/2015/11/RooftopUnitsFDD_FinalResearchSummary1.pdf

The capabilities of available AFDD products can vary substantially, especially since many offerings are customizable to fit the system design, equipment types, and other attributes of the specific building.[39] Table 35 highlights some of the capabilities offered by several AFDD systems for RTUs, including those that are basic product capabilities and those premium cost-added features that can be added for the specific application. As, discussed above, AFDD products must balance the value that additional features offer with their additional cost and complexity. Some products, such as the Low-Cost SMDS developed by PNNL, offer fewer number of features to lower costs, but can still provide the core functionality necessary to improve maintenance practices and achieve energy savings.

Table 35. Example Capabilities of Select AFDD Systems for RTUs

AFDD Capability	FDSI Insight / Sentinel	Clima-Check	Low-Cost SMDS	Low-Cost NILM	Virtjoule
Low Airflow	✓	✓		✓	✓
Low/High Charge	✓	✓		✓	✓
Sensor Malfunction	✓	✓			+
Economizer Fault	✓	+			✓
Compressor Cycling	✓	✓	✓	✓	✓
Excessive Operating Hours	✓	✓	✓		✓
Performance Degradation	✓	✓	✓	✓	✓

[39] Katipamula, Srinivas, and Michael R. Brambley. 2005a. "Methods for Fault Detection, Diagnostics and Prognostics for Building Systems – A Review Part I." International Journal of Heating, Ventilating, Air Conditioning and Refrigerating Research, 11(1):3-25. PNNL, Richland, WA. Katipamula, Srinivas, and Michael R. Brambley. 2005b. "Methods for Fault Detection, Diagnostics and Prognostics for Building Systems – A Review Part II." International Journal of Heating, Ventilating, Air Conditioning and Refrigerating Research, 11(2):169-188. PNNL, Richland, WA.

AFDD Capability	FDSI Insight / Sentinel	Clima-Check	Low-Cost SMDS	Low-Cost NILM	Virtjoule
Insufficient Capacity	✓	✓	✓		+
Incorrect Control Sequence	✓	✓		✓	✓
Lack of Ventilation	✓				+
Excess Outdoor Air	✓	+			+
Control Problems	✓	✓			✓
Failed Compressor	✓	✓		✓	✓
Stuck Damper	✓	✓			+
Slipping Belt	✓	✓			✓
Leaking Valves	✓	✓			+
Failed Unit	✓		✓	✓	✓

Note: ✓ represents basic product capability + represents premium product capability
Source: New Buildings Institute. 2013. "Rooftop Units Fault Detection and Diagnostics – Part of the Evidence-based Design and Operations PIER Program." Prepared for California Energy Commission. March 2013. Available at: https://newbuildings.org/wp-content/uploads/2015/11/RooftopUnitsFDD_FinalResearchSummary1.pdf

AFDD vendors offer a variety of hardware, software, and services to their customers, similar to EMIS vendors. Hardware typically includes one or more sensors (wired or wireless) and communication equipment (e.g., WiFi, cellular, Ethernet). Monitoring software may be located onsite or through cloud computing systems. In addition, many offerings include remote monitoring for both the building staff and service provider, and may connect directly to the service technician to expedite the repair process.

8.1.3 Relevant CBI Work and Resources

Various CBI and ET projects have focused on AFDD systems for RTUs and AHUs over the last several years. Table 36 summarizes AFDD-related projects, while Table 37 summarizes BTO Sensors and Controls Projects, which will ultimately support AFDD systems.

Table 36. DOE AFDD Projects for RTUs and AHUs

Title	Lead Performers	Overview	Report Link
AHU FDD in Small and Medium Sized Commercial Buildings	CBEI-Drexel University, PNNL	Develop and demonstrate cost-effective and VOLTTRON-compatible AFDD for AHUs	Link
Fault Detection and Diagnostics (FDD) for Advanced RTUs	CBEI-URTC, CBEI-Purdue	For advanced RTUs, implement and assess low- cost, embeddable AFDD systems	Link
Pre-Commercial Demonstration of Cost-effective Advanced HVAC Controls and Diagnostics for Medium-size Buildings	CBEI-UTRC	Demonstrate cost-effective, scalable installation of advanced building and HVAC control and AFDD solutions.	Link

Title	Lead Performers	Overview	Report Link
Virtual Refrigerant Charge Sensing and Load Metering	CBEI-Purdue, CBEI-UTRC, Lennox	Extend RTU virtual sensor methods for refrigerant charge, cooling capacity, and unit power to RTUs having micro- channel condensers	Link
Demonstrations of Integrated Advanced RTU Controls and AFDD	PNNL, Transformative Wave, NorthWrite Universal Devices	Show that integrating advanced controls and AFDD systems could result in significant savings and persistence for RTUs at low cost	Link
VOLTTRON Analytics for RTUs	PNNL	Open source algorithms and automated continuous commissioning algorithms for RTUs, with potential adaptation for AHUs; RTU AFDD algorithms meet CA Title 24 requirements	Link

Source: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

Table 37. DOE Sensors, Controls, and Transactional Network Projects

Title	Lead Performers	Report Link
VOLTTRON	PNNL	Link
BEMOSS	Virginia Tech Advanced Research Institute	Link
Controls and Communication Integration	LBNL, U.S. India Joint CBERD	Link
Sensors, Controls, and Transactive Energy Research	PNNL	Link
University-Industry-National Laboratory Partnership to Improve Building Efficiency by Equipment Health Monitoring with Virtual Intelligent Sensing	ORNL	Link
Low-cost Wireless Sensors for Building Monitoring Applications	ORNL	Link
Building Re-tuning	PNNL	Link
Smart Buildings Equipment Initiative	PNNL, NREL	Link
Transforming Ordinary Buildings into Smart Buildings via Low-Cost, Self-Powering Wireless Sensors and Sensor Networks	Case Western Reserve University, Cleveland, OH	Link
Retro-commissioning Sensor Suitcase Commercialization Pilot Project	PNNL, LBNL, ORNL	Link

Source: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

8.1.4 Barriers

AFDDs systems for RTUs and AHUs emerging onto the market today could greatly ease maintenance practices and improve the performance and efficiency of commercial HVAC systems, but several barriers exist before widespread adoption. Table 38 highlights several key technical and market barriers.

Table 38. Barriers – AFDD Systems for RTUs and AHUs

ID	Barrier	Description
1	Lack of availability and awareness	While several manufacturers and vendors offer AFDD products today, most are not widely available as a simple add-on for most equipment purchases or tune-ups. Many manufacturers, even within California, may not highlight the AFDD features of their products, and may not offer AFDD capabilities in other regions. In addition, HVAC contractors may not be aware of system capabilities or communicate the value of potential retrofit AFDD systems to customers.
2	Difficulty quantifying benefits	AFDD can provide benefits over the life of equipment, but forward-looking energy savings and non-energy benefits are difficult to predict for different equipment types, operating conditions, etc. This is especially problematic when estimating the cost-effectiveness of AFDD systems to justify their purchase for a project.
3	Lack of understanding of AFDD capabilities	Within the HVAC industry, standard definitions and test methods for various AFDD features are still under development. Determining the proper fault thresholds and to avoid false alarms, missed faults, etc. or the right algorithms to avoid misdiagnosis is difficult, and will likely never be perfect. Building owners and staff have low tolerance for false alarms or frequent faults and may not understand what the AFDD system is providing through faults.
4	Difficulty of integration with legacy systems	Especially for AHUs that operate throughout medium-to-large buildings, the buildings already have some building automation features in place, and integrating with the existing system or adding additional sensors can be difficult in retrofit situations.
5	Perception of high costs	AFDD systems carry steep upfront costs for hardware, software, installation, etc., in the range of several hundred dollars for RTUs, to several thousand dollars for AHU systems. These upfront costs are significant relative to a single service call for maintenance.
6	Limited time and resources for building operators	Especially for small commercial buildings, the transition from seasonal maintenance to periodic monitoring and more intermittent maintenance with AFDD systems adds another responsibility to already limited and stretched resources.
7	Alters traditional maintenance practices	Building owners, maintenance staff, and HVAC technicians are accustomed to the predictability of a seasonal or annual maintenance schedule, and AFDD could alter the timing and scope of maintenance calls significantly. While the net outcome will be beneficial, this still moves building owners and operators out of their established zones of comfort and predictability.
8	Data integration challenges	For many systems, especially those that rely on BAS sensor data, data integration is costly and time consuming, which makes the value proposition much more challenging. Even for systems that use their own sensors, integrating AFDD output with systems that the building operators already use can be challenging and costly to train operators to consult yet another information system during their daily routine.
9	System security	Wireless sensor technologies, including those incorporated into AFDD systems, may pose security issues. Some building managers mistrust wireless systems in environments that require extremely high system reliability.

ID	Barrier	Description
10	Lack of contractor training	Strong contractor engagement is vital to successful deployment of AFDD, but has been lacking in utility efficiency programs, but this seems to be due to a lack of training on the technology. Utility efficiency program experience suggests that many lack the technical knowledge to optimally install equipment and guide users on operation. Further, the business model for selling AFDD retrofit equipment is distinct from their normal model of selling equipment and they may also lack the comprehensive understanding of the value proposition to be able to sell the product effectively.
10	Incentive structures	Current downstream (direct-to-customer) incentives are seemingly insufficient to motivate contractors to engage. Their involvement is vital to successful deployment. Midstream- or upstream-rebate delivery channels may be considered to help drive contractor engagement.

Source: Material developed by Navigant, DOE National Laboratory reviewers, and fall 2015 workshop stakeholder participants.

8.1.5 Other Focus Programs and Cross-Cutting Opportunities

In addition to BTO, a multitude of researchers, standards organizations, and other stakeholders across the HVAC and commercial building industries have identified the need for widespread integration of AFDD systems into RTUs and AHUs to enable commercial building energy savings. These organizations support initiatives to further develop the AFDD algorithms that could be used with lower installation cost and complexity. Table 39 highlights some of the activities that other government and non-government organizations have conducted in support of AFDD for RTUs and AHUs.

Table 39. Other Programs Supporting AFDD Systems for RTUs and AHUs

Provider	Program Highlights
Universities	R&D for AFDD systems, sensors, and algorithms • Massachusetts Institute of Technology • Purdue University • Texas A&M • University of Nebraska • Drexel University
National Laboratories	AFDD system development and demonstration, with several projects highlighted in Table 34 • PNNL • LBNL • National Institute of Standards and Technology • ORNL
Western HVAC Performance Alliance (WHPA)	Developed FDD Industry Roadmap developed by WHPA FDD Committee
Western Cooling Efficiency Center (WCEC)	University of California Davis WCEC provides support to California (Investor-Owned Utilities) IOUs' HVAC Technology and System Diagnostics Advocacy Program and to the WHPA FDD Subcommittee

Provider	Program Highlights
ASHRAE	• TC 7.5 – The Smart Buildings Technical Committee of ASHRAE is responsible for programs, standards, research, and handbook related to FDD. • SPC 207P– The Standards Project Committee is tasked with developing the "Laboratory Method of Test of Fault Detection and Diagnostics Applied to Commercial Air Cooled Packaged Systems" • SSPC 90.1 – The Mechanical Subcommittee RTU Working Group has been focused on RTU issues as they relate to the 90.1 Standard • SSPC 189.1 – This standard for high-performance buildings could be a tool for disseminating information about FDD and encouraging adoption • Guideline 36P – High-Performance Sequences of Operation for HVAC Systems

California Energy Commission Electric Program Investment Charge	• Title 24-2016 building energy codes require RTUs >4.5 tons to have AFDD systems covering airflow, economizer operation, and sensor failure.
	• Automated HVAC FDD Commercialization Program
	  ○ Project team works with major manufacturers to develop systems and controls
	  ○ Includes field demonstrations to document energy performance and cost advantages of the systems
	  ○ HVAC FDD Tool marketed by Architectural Energy Corporation was demonstrated at state university sites

California IOUs	California IOUs conduct research into energy efficiency issues through field studies, support for emerging technologies, and other activities, and promote adoption through incentive programs and stakeholder outreach.
IEA Annexes	The International Energy Agency has sponsored a set of research programs or annexes to develop, implement, and test FDD algorithms
ESource	ESource has conducted a review of program participation for advanced RTU controllers to elucidate specific barriers to the adoption of these controllers in utility service areas.

Source: WHPA. 2013. "Onboard and In-Field Fault Detection and Diagnostics—Industry Roadmap." Western HVAC Performance Alliance. July 10, 2013. Available at: http://www.performancealliance.org/Portals/4/Documents/CommitteeWorkspace/AFDD/WHPA%20Fault%20Detection%20and%20Diagnostics%20(FDD)%20Roadmap.pdf

8.2 Technical Opportunities: AFDD for RTUs and AHUs

Workforce development and training approaches will be important to maximize energy savings created using AFDD with HVAC systems. Lack of engagement from contractors in the implementation of AFDD opportunities could be remedied through dialogue with industry stakeholders on the topic and the entities listed in Table 8-9 are well aligned to initiate this dialogue. Research based on current project implementations will respond to questions about the benefits and effectiveness of AFDD. Additional investigation into specific integration, connectivity and barriers to automation and/or control will inform additional development efforts.

9 Analysis–Advanced Supermarket Refrigeration Systems

9.1 Evaluation of Current Market Landscape – Advanced Supermarket Refrigeration Systems

9.1.1 Key Sectors and Applications

Several major commercial building types commonly use field-erected refrigeration systems, including food sales (grocery stores, supermarkets, etc.) and food service establishments. A majority of the installed base of refrigeration systems in commercial spaces is in food sales applications.[40] Commercial refrigeration consumes significant energy, making food retail establishments very energy-intensive building types. Annual energy use values range from approximately 100,000 kilowatt-hours (kWh) per year to 1.5 million kWh/year, depending on store size and location. Within those buildings, it is estimated that refrigeration system energy use comprises up to 50% of the whole-store energy consumption.[41] While commercial refrigeration equipment can be split into several major types, the bulk of the energy use is attributed to supermarket refrigeration. Figure 10 shows a breakdown of commercial refrigeration energy use by system type.

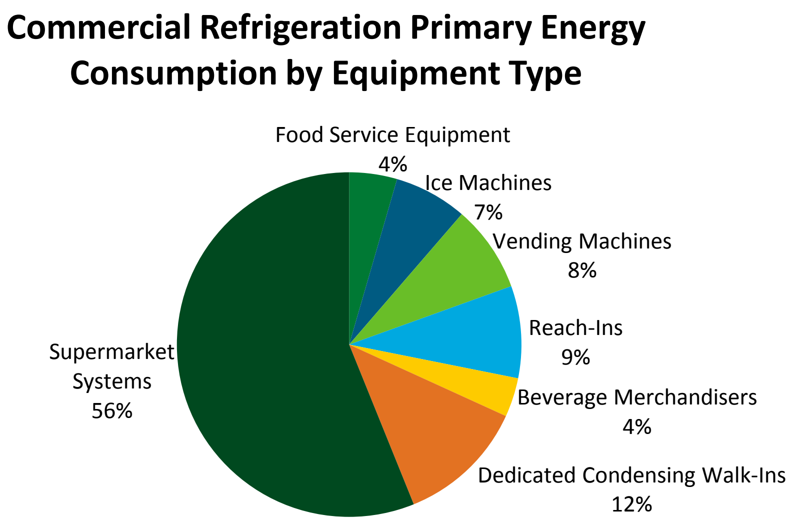

Figure 10. Commercial refrigeration primary energy consumption by equipment type (2008)
Source: Navigant (2009)[40]

Supermarket refrigeration systems consist of several major components and subsystems: point of cooling (e.g., display case, walk-in), compressors, condenser(s), control systems, and interconnecting piping. Figure 11 shows a representative schematic of a typical supermarket refrigeration system. A supermarket with roughly 50,000 square feet of floor area uses about 60 display cases to display fresh and frozen food products. These cases may be open (typically used for fresh produce, dairy, etc.) or closed (typically used for frozen food). Except for some small, standalone display cases, a large majority of supermarket cases are connected to remote-condensing units as part of the storewide refrigeration system. For this common configuration, a set of compressors (i.e., compressor rack) distributes refrigerant throughout the supermarket to refrigerator and

[40] Navigant Consulting. "Energy Savings Potential and R&D Opportunities for Commercial Refrigeration." (2009): US Department of Energy, 23 Sept. 2009.
http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf.
[41] ICF International, Revised Draft Analysis of U.S. Commercial Supermarket Refrigeration Systems
Available at: https://www.epa.gov/sites/production/files/documents/EPASupermarketReport_PUBLIC_30Nov05.pdf

freezer display cases and external condenser(s), usually located on the roof. The refrigerant travels throughout the supermarket in a circuit of insulated piping assembled in the field. In addition to display cases, supermarkets typically also have several walk-in coolers and freezers for display of high-volume items (e.g., milk, eggs), storage, and ripening. Various controls for individual cases, walk-ins, compressor racks, and condensers ensure the supermarket refrigeration system operates safely and efficiently at proper temperatures for each refrigeration need.

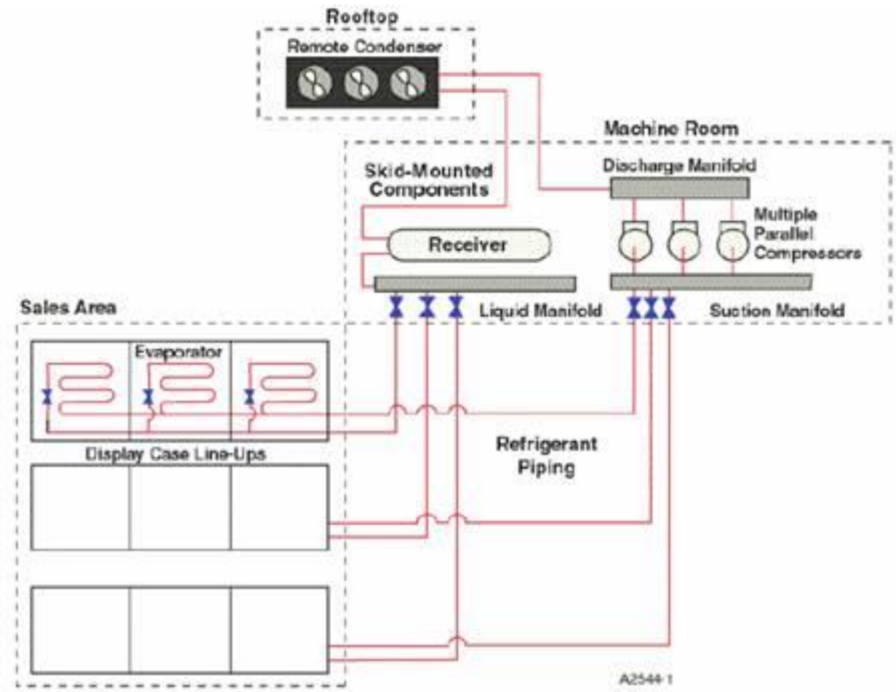

Figure 11. Typical supermarket refrigeration system configuration
Source: Image courtesy EPA GreenChill Partnership[42]

Energy savings for supermarket refrigeration systems can be achieved by increasing the efficiency of core refrigeration equipment (e.g., improvements to compressors and heat exchangers or using alternative refrigerants and system designs), and by decreasing the energy consumption and thermal losses in ancillary systems (e.g., door and insulation improvements). In addition, efficiency improvements to ancillary systems that dissipate heat within the chilled volume (e.g., lighting, anti-sweat heaters, fans, defrost) offer compound energy savings through primary efficiency improvement and secondary heat load reduction.

Common ways to improve the energy efficiency and performance of supermarket refrigeration systems include:

- **Closed Display Case Retrofits**: Open display cases tend to be more attractive and accessible to consumers, but they are significantly less energy-efficient than closed display cases. As such, more supermarkets and chains are moving toward increasing the number of closed cases, either through replacement of old open cases or, where possible, through door retrofits. To save energy and cut costs, stores may choose to install transparent doors on existing open cases. DOE estimates that door retrofits on existing open cases will save between 50% and 80% of system electricity consumption, not including any savings in space conditioning energy use. Additionally, this technology incurs

[42] EPA GreenChill Advanced Refrigeration Accessed: http://www2.epa.gov/greenchill/advanced-refrigeration

additional non-energy-related benefits, such as increased product lifetimes due to tighter temperature control.

- **Display Case Lighting and Controls**: Display cases use internal lighting to allow customers to see merchandise, but creates a heat load within the refrigerated space. Historically, display cases have had T8 fluorescent lights, but many retrofit packages and most new display cases offer a wide variety of LED lighting options at reasonable cost. Timers, motion controls, and dimmers allow display case lights to be switched off or dimmed automatically based on the time of day, customer proximity, or the ambient lighting level for additional savings. Reducing lighting consumption has a direct benefit for lower lighting consumption, while also decreasing the cooling load on the refrigeration system.
- **Display Case Anti-Sweat Heater and Defrost Controls**: Display cases also may make use of anti-sweat heaters to prevent condensation from forming on the display case doors, frames, and walls. Instead of continuously operating anti-sweat heaters at full power, on-demand anti-sweat heater controls can be used to reduce anti-sweat heater electricity consumption based on the conditioned space dew point temperature. In addition, on-demand anti-sweat heater controls can reduce overall refrigeration system electricity consumption, since less heat is emitted into the refrigerated space. Similarly, advanced defrost controls can reduce the number of defrost cycles by monitoring the status of evaporator coils and initiative defrost only when necessary.
- **Refrigeration System Controls**: A variety of refrigeration system control options are available to monitor and adjust the operating cycles of the compressor rack, condensers, and other equipment from a centralized control system. These more sophisticated energy management systems offer more accurate temperature control by monitoring storewide display case temperatures and using solid-state controlled suction valves, evaporator pressure regulators, electronic expansion valves, variable-speed fans, and other technologies to optimize performance.

Beyond energy efficiency during proper operation, supermarket refrigeration systems have large refrigerant charges and often experience high leakage rates, which degrade performance and efficiency while increasing operations and management costs. Some sources estimate leakage for some systems to be as high as 25% each year (EPA, 2015 and EPA, 2016). The working fluids utilized in the majority of supermarket refrigeration systems today consist of hydrofluorocarbons (HFCs) or blends thereof. These refrigerants are known as third-generation refrigerants,[43] and are not harmful to the Earth's ozone layer, but possess high GWP values.

The U.S. Environmental Protection Agency's (EPA) Significant New Alternatives Policy (SNAP) program is the governing program which maintains authority over the acceptability of substances for use across multiple end-use applications, including refrigeration. Recently, EPA SNAP initiated transitions away from substances with high GWP values. The most notable SNAP action today has been the publication of a final rule in July 2015 removing multiple high-GWP HFCs, such as R-404A and R-507A, which are commonly found in commercial refrigeration systems, from acceptable use as soon as 2017.[44] More aggressive action has been taken in the European Union, in the form of F-Gas (fluorinated gas) regulations, which will stringently curb the use of HFCs.[45]

The recent regulatory action on high-GWP refrigerants, coupled with an increasingly environmentally conscious consumer base, has motivated equipment manufacturers and store operators to seek lower-GWP alternatives that still allow them to maintain necessary levels of temperature control and energy performance.

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[43] The first generation of refrigerants consisted of volatile fluids such as ethers, alongside some natural compounds such as propane, while the second generation consisted of synthesized fluorochemicals, most notably chlorofluorocarbons.

[44] EPA SNAP: "Change of Listing Status for Certain Substitutes Under the Significant New Alternatives Policy Program; Final Rule"
Available: https://www.gpo.gov/fdsys/pkg/FR-2015-07-20/pdf/2015-17066.pdf

[45] European Commission, Climate Action – Fluorinated Greenhouse Gases.
Available: http://ec.europa.eu/clima/policies/f-gas/index_en.htm

As such, several emerging refrigerants, in different stages of commercialization in the U.S. market, have been identified. These include:

- **Carbon dioxide:** Carbon dioxide was one of the very first working fluids to be used in a vapor-compression refrigeration cycle, but was largely displaced by synthetic refrigerants with more desirable thermophysical properties. This refrigerant is attractive due its heat transfer capacity, low GWP (1, by definition), and widespread availability at high purity. Transcritical CO_2 systems produce substantial amounts of high-quality waste heat, which can be recovered for use in space-heating and water heating applications. The good low-ambient performance and heat recovery opportunity has made these systems the near standard in northern Europe, with significant market penetration in Canada as well. Transcritical CO_2 is also prevalent in Japan. Within the United States, the first such system was commissioned in Maine in 2013, with additional systems since having been placed in New York, Northern California, and elsewhere.[46,47]
- **Hydrofluoroolefins (HFOs) and HFO blends:** HFOs are a family of synthetic refrigerants which have been under development by major international chemical companies over the past number of years. The most widely known HFOs are HFO-1234yf and HFO-1234ze(E), which are manufactured and distributed by various suppliers under several different trade names. These substances were developed as substitutes (in some instances, drop-in replacements) for legacy HFC refrigerants and possess GWP values in the single digits. HFOs are also sold blended, generally with HFCs, producing mixtures that have intermediate aggregate GWP values between those of the pure HFOs and the HFCs, but more closely mimic the thermophysical properties of HFCs than would a pure HFO. In addition, several pure HFO refrigerants are mildly flammable on their own, and these HFOs can be mixed with HFCs to produce non-flammable refrigerant blends. HFO refrigerants and their blends have broad application to a wide variety of end uses, but their use to date in commercial refrigeration applications has been limited; however current regulations will soon lead to their accelerated use. In Europe, only a few stores employ HFO systems in customer-facing applications, while in the U.S. market, exploration of these working fluids has been limited to laboratory tests.[48,49,50] However, effective January 2017 per US EPA SNAP regulations, the use of R-404A (a common refrigerant found in commercial refrigeration systems) is no longer permitted in new supermarket refrigeration systems, and alternative lower-GWP refrigerants such as R-407A or the HFO blends R-448A or R-449A must be used.
- **Ammonia:** Ammonia has been used in industrial applications such as process chilling and cold storage warehouses for decades. The supplier and technician communities are strong, costs are low, and energy performance is excellent. However, the main deterrents to the use of ammonia are its toxicity and flammability, mitigation of which requires implementation of numerous safety measures and clearance of regulatory hurdles. This is amplified in a consumer-facing application such as a retail store. There is an anecdotal aversion to the refrigerant's use in public areas by many in the refrigeration community due to past incidents in industrial settings. One method to minimizing the risk

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46 DOE BBA: "Case Study: Transcritical Carbon Dioxide Supermarket Refrigeration Systems"
Available: http://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/Transcritical_CO2_Supermarket_Refrigeration_Systems.pdf

47 Emerson Climate Technologies: "Commissioning a CO_2 System"
Available: http://www.emersonclimate.com/en-us/About_Us/News/Events/E360-Annual-Conference/Documents/MAGA-Tuesday-1100-Kolstad.pdf

48 *ACHR News*: "Italian Supermarket Claims Big Energy Gains from HFO/CO2 Cascade and Heat Recovery"
Available: http://www.achrnews.com/articles/131939-italian-supermarket-claims-big-energy-gains-from-hfoco--cascade-and-heat-recovery

49 United Nations Environmental Programme: Low-GWP Alternatives in Commercial Refrigeration: Propane, CO_2, and HFO Case Studies
Available: http://www.unep.org/ccac/portals/50162/docs/Low-GWP_Alternatives_in_Commercial_Refrigeration-Case_Studies-Final.pdf

50 U.S. Department of Energy: "Working Fluids: Low Global Warming Potential Refrigerants"
Available: http://energy.gov/sites/prod/files/2014/10/f18/emt13_abdelaziz_042414.pdf

of using ammonia has been to utilize the refrigerant in a "cascade" configuration, in which all the ammonia is kept outside of the building in a closed loop, and a secondary loop (generally of carbon dioxide) is used for the heat transfer out of the store. Ammonia-CO_2 cascade systems have been successfully piloted in several commercial settings in the United States, including a grocery store in California and a commissary on a U.S. Air Force base in Texas.[51,52]

To date, only a small percentage of the approximately 37,000 supermarkets in the U.S. have transitioned to refrigeration systems using alternative refrigerants.[53] Nevertheless, their adoption is growing steadily (shown in Table 40), with the number of supermarkets using CO_2 refrigeration systems having more than doubled over the period of 2013-2015.

Table 40. U.S. Grocery Stores Using CO_2 Refrigeration Systems

Type	2013	2014	2015
Transcritical CO_2 Systems	2	14	52
Cascade CO_2 Systems	113	190	199
Total	115	204	251

Shecco. 2015. "Guide to Natural Refrigerants in North America – State of the Industry."[53]

Beyond simply changing the refrigerant gases to lower-GWP refrigerants, several leak detection technologies are available to monitor supermarket refrigeration systems, allowing for the quick detection and repair of leaks. Direct methods use air sniffers or infrared sensors to sample multiple refrigeration zones for the presence of a refrigerant, signaling a leak. Indirect methods leverage existing sensors and data from the central control system to track temperatures, pressures, and other attributes and identify leakage events when refrigeration system performance deviates. In each case, leak detection technologies support system performance and efficiency, reduce O&M costs, and decrease the need to purchase additional refrigerant.[54]

9.1.2 Major Manufacturers

Individual components of a supermarket refrigeration system often come from different manufacturers and are assembled on-site by mechanical contractors. A range of domestic and global manufacturers offer systems or components designed for conventional and alternative refrigerants. Due to the custom nature of supermarket-scale refrigeration systems, the means of sourcing of these systems and their necessary components can vary widely from customer to customer. Typically, larger players in the market provide complete refrigeration systems, engineered on a site-specific basis to fit the customer's needs, and including compressor racks, condensers, display cases, and associated controls. These players in turn source from other component-level suppliers.

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[51] EPA GreenChill Partnership, "Ammonia Cascade Systems"
Available: https://www.epa.gov/sites/production/files/documents/GC_Webinar_AmmoniaCascade_2012.11.15.pdf
[52] EPA SNAP, "Low-GWP Alternatives in Commercial Refrigeration"
Available: https://www.epa.gov/sites/production/files/2015-10/documents/deca_commercial_refrigeration_case_study.pdf
[53] Shecco. 2015. "Guide to Natural Refrigerants in North America – State of the Industry." Accelerate Magazine. September 2015. Available at: http://publication.shecco.com/publications/view/guide-north-america-2015
[54] Wallace, John. Emerson Climate Technologies. Available at:
http://www.emerson.com/resource/blob/168144/7d9d792f37b5bdc6ffc6847c03c1342d/article---industry-set-sights-on-reducing-refrigerant-leaks-data.pdf

Table 41 lists major suppliers within the supermarket refrigeration system market. These include manufacturers of components, entire systems, controls, refrigerants, and display case door retrofit kits.

Table 41. Major Industry Players – Advanced Supermarket Refrigeration Systems

Company	Full Systems	Compressors	Condensers	Display Cases	Case Retrofits	Controls	Refrigerants
Anthony Intl.					x		
Bitzer		x					
Carel						x	
Carlyle		x					
Carnot	x						
Danfoss		x				x	
DuPont							x
Emerson		x				x	
GEA		x				x	
Heatcraft			x				
Hillphoenix	x			x	x		
Honeywell						x	x
HTPG			x				
Hussmann	x		x	x	x		
Johnson Controls						x	
Kysor/ Warren				x			
Panasonic		x		x			
REMIS					x		
Zero-Zone	x			x			

*In December 2015, Panasonic agreed to purchase Hussmann Corp.; however, the company still operates as an independent brand and is thus listed as such here.
Source: Navigant Consulting. "Energy Savings Potential and R&D Opportunities for Commercial Refrigeration." (2009): US Department of Energy, 23 Sept. 2009.
http://apps1.eere.energy.gov/buildings/publications/pdfs/corporate/commercial_refrig_report_10-09.pdf.

9.1.3 Relevant CBI Work and Resources

Table 42 lists CBI activities supporting energy efficiency measures and alternative refrigerants for supermarket applications.

Table 42. DOE Efforts Supporting Advanced Supermarket Refrigeration Systems

Project Title	Report Link
ASHRAE Refrigeration System Commissioning Guide	Link
Hannaford Transcritical Carbon Dioxide Refrigeration Case Study	Link
ORNL: High-Efficiency, Low-Emission Refrigeration System	Link
Grocery Store Advanced Energy Design Guide	Link
Refrigerant Playbook: Natural Refrigerants	Link
Refrigerated Display Case Controls (Webinar)	Link
Commercial Buildings Resource Database - Commercial Building Partnerships	Link
Guide for Retrofitting of Open Refrigerated Display Cases with Doors	Link
Open Case Retrofit Savings Case Study: Fresh & Easy	Link
Open Case Retrofit Savings Calculator	Link
M&V of a Liquid Refrigerant Pump System Retrofit	Link
High Efficiency Evaporator Fan Motors	Link
High Efficiency, Low Emission Refrigeration System	Link
Case Study: Walmart — Saving Energy, Saving Money Through Comprehensive Retrofits	Link

Sources: Provided in individual links; table developed by Navigant and DOE national laboratory subject matter experts.

9.1.4 Barriers

New technologies for supermarket refrigeration systems encounter numerous technical and market barriers to implementation in U.S. grocery stores. Table 43 highlights several major barriers for advanced supermarket refrigeration systems.

Table 43. Barriers – Advanced Supermarket Refrigeration Systems

ID	Barrier	Description
1	Limited number of system and component suppliers / interoperability	The number of suppliers of advanced refrigeration systems and components is limited, and production volumes are comparatively low. This provides buyers with limited options, constraining their ability to apply price pressure or request specific custom features. In addition, controls may not be compatible with all suppliers and system designs.
2	Lack of service infrastructure	There is a significant shortage of qualified technicians to service even legacy, established HFC systems. Introduction of new system designs and refrigerants heightens this barrier, as existing service technicians do not have experience with the systems, and training services may yet not have developed curricula for use in educating technicians on these emerging technologies.

ID	Barrier	Description
3	First cost	Advanced supermarket refrigeration systems incur a significant first-cost premium over legacy HFC systems. This is due to several factors, including low production volume on the supplier side, a need for specialized engineering resources when specifying systems, and inherently costlier componentry within the systems themselves. In industries with extremely low margins and limited operating capital, such as food retail, first-cost sensitivity is high.
4	Regulatory and market uncertainty	The past years have seen many changes in the regulatory landscape surrounding refrigeration equipment, both on the energy and GWP impact fronts. Having been affected by multiple rounds of refrigerant transitions and energy conservation standards, operators are seeking solutions with stability and long-term viability. Because no single alternative refrigerant has emerged as the ideal solution, many potential adopters pause for fear of potentially making the "wrong" choice and being saddled with obsolete equipment for a generation.
5	Product and occupant safety	Grocery store owners and managers must maintain safe environments for food products and shoppers. Several alternative refrigerants introduce flammability and/or toxicity concerns, especially when supermarket refrigeration systems are prone to leakage. In addition, advanced case and system controllers adjust operations to measured conditions, rather than overly conservative "always on" settings.
6	Downtime	In some cases, adding controls to existing units requires refrigeration systems to be shut down for the duration of the installation. Any downtime presents a significant barrier for consumers. Downtime also can risk perishable products if those products are not relocated.
7	Lack of applicable information	Designers find it hard to obtain and compare quantitative data on specifications, costs, and complete product information regarding advanced supermarket refrigeration systems due to the custom-built nature of most applications.
8	Concerns Over Impacts on Sales	Some supermarket operators believe that installing glass doors on open cases or installing dimmers for display case lights will make merchandise less visible and less accessible to customers, thereby affecting product sales. This belief lingers even though some studies have shown the sales impact to be minimal or even positive, particularly when considering the value of conserved energy.[55]

Source: Material developed by Navigant, DOE national laboratory reviewers, and fall 2015 workshops stakeholder participants.

9.1.5 Other Focus Programs and Cross-Cutting Opportunities

Numerous energy efficiency programs at electric utilities offer custom and deemed rebates for advanced supermarket refrigeration systems, including specific rebates for display case retrofits, display case lighting, adaptive controls, and other measures. Table 44 provides a snapshot of some of the programs and activities that support market adoption of refrigeration controls.

[55] *ASHRAE Journal*, "Doored Display Cases – They Save Energy, Don't Lose Sales". Fricke, Brian A. and Bryan R. Becker. September 2010.

Table 44. Utility Programs Supporting Advanced Supermarket Refrigeration Systems

Provider	Program Highlights	Source
PG&E	• Refrigeration Rebate Catalog for businesses includes refrigeration control systems. • Focus on adaptive refrigeration controls. • EnergySmart Grocer Rebate including a rebate of $70/linear ft. for retrofit door installations.	Link Link
SMUD	• Energy Efficiency Measures Demonstrations for Refrigeration Controls. • Incentives covering up to 80% of installation cost.	Link
Baltimore Gas and Electric	• Small Business Energy Solutions program provides refrigeration measures and financial incentives up to 80% of refrigeration control retrofits for customers who have billing demand of 60 kW or less.	Link
Connecticut Light and Power	• Small Business Energy Advantage Program offers an energy assessment, and incentives for control retrofits.	Link
Southern California Edison (SCE)	• Existing Building Direct Install Program provides consultation with an energy efficiency contractor to recommend refrigeration upgrades, including appropriate controls. • Express Energy Management Solutions incentives, offered to consumers planning to install retrofit doors, as well as those who have done so recently	Link Link
Arizona Public Service (APS)	• Express Solutions program offers incentives of up to 90% of project costs for refrigeration upgrades including controls.	Link
AVISTA Utilities	• EnergySmart Grocer Rebate including a rebate of $85/linear ft. for retrofit door installations.	Link
BPA	• EnergySmart Grocer Rebate including a rebate of $60/linear ft. for retrofit door installations.	Link

During the development of this plan, BTO was not able to identify any significant efforts to date by third-party programs (utilities, REEOs, etc.) in studying, promoting, or incentivizing advanced supermarket refrigeration systems using alternative refrigerants in the U.S. Manufacturer developed literature and case studies developed by manufacturers and/or market research firms does exist. However, energy-efficiency organizations and utilities appear to be taking a wait-and-see approach, highlighting the degree of uncertainty and hesitation in the market surrounding these alternative refrigerants.

9.2 Technical Opportunities: Advanced Supermarket Refrigeration Systems

EPA's SNAP program and the Montreal Protocol will impact the refrigeration system efficiency as refrigeration policies and regulations evolve. Based on developments in these programs, ongoing independent field validation (or in the case of some alternative refrigerants, laboratory data) will provide the data and performance information to support additional technical work. Current questions exist regarding the performance of advanced refrigeration systems in multiple climates and applications as well as commissioning, leak detection and maintenance. Component-to-component laboratory and/or field testing may inform additional research necessary for ease of integration and interoperability. Additionally, workforce development and training will help existing and new qualified technicians install new systems and conduct system analytics to ensure optimal performance.

10 HITs for High-Performance New Construction

The use of connected, efficient component technologies and systems in new construction will create data to support whole building optimization and potential autonomy of building operations. While new buildings account for only 2% of U.S. commercial floor space each year, the cumulative addition of new buildings from 2017-2030 will account for approximately 30% of all commercial floor space in 2030.[56] By targeting new construction applications, HITs could substantially impact national commercial building energy consumption while also enabling the collection and evaluation of data to better understand which technology areas will provide the most impact in existing buildings.

BTO held a stakeholder workshop in 2017 to identify areas where high-performance new construction can impact the development of advanced technologies. While the benefits will change for different technologies, the workshop participants discussed the following concepts:

- **Cost-Effectiveness**: In existing buildings, energy efficiency upgrades are weighed based on component-level baseline versus advanced technology cost and performance. Often, the upfront cost of advanced and emerging technology outweighs the energy savings benefit or the payback does not fall within business thresholds. For high performance new construction projects, systems are designed and sized while considering on trade-offs between building loads, construction/upfront cost and long-term energy and operational savings. This helps bring to light the long-term cost implications of less efficient technology components and systems, triggering the incorporation of advanced emerging technologies and system design.
- **Whole Building Optimization**: Advanced technologies can change the way the building operates to reach higher levels of performance. In many cases, these differences affect the existing infrastructure (e.g., duct design, roof support, power availability, compatibility with equipment and controls). In new construction, advanced technologies and systems are integrated directly into design and construction, simplifying installation costs. In addition, technologies that affect building loads, such as building envelope and lighting improvements, can have a compounding effect on project cost since certain systems can be downsized, reducing costs further.
- **Connectivity:** Advanced technologies and building systems leverage connectivity and automation to optimize performance. In existing buildings, connectivity is achieved incrementally over time as new connected products are added during construction upgrades. Currently, this requires time consuming and complicated, expert-driven integration. In new construction, connected components can be incorporated holistically so that data streams feed into analytics, optimization, and autonomous operations from design to occupancy and operation.
- **Reduced Disruption**: Building owners/operators avoid downtime to minimize impact on business tenants, customers, and occupants. Advanced technologies may be manufactured in smaller quantities, thus requiring longer sales processes and lead times, which leads to them not being a part of the equation for emergency replacement at equipment failure. New construction can accommodate advanced technologies in the much longer design and selection process, so long as design teams and constructors coordinate correctly with manufacturers. Additionally, because the building is not operational yet, there is also better opportunity to properly commission the system and ensure proper performance.

Table 45 highlights the current list of HITs as these advanced technologies may benefit from incorporation into new construction projects. For example, installing an advanced supermarket refrigeration system using alternative refrigerants in a new building is significantly less complicated than in an existing building. In a retrofit situation, the supermarket would experience extended downtime as technicians remove and replace every display case and other component throughout the store. For an industry that has low margins like

[56] EIA. 2017. "2017 Annual Energy Outlook." Tab 5. Commercial Sector Key Indicators and Consumption

supermarkets, this lost revenue could be the deciding factor even if the advanced refrigeration system has no incremental cost.

Table 45. Attractive Characteristics of Current HITs for New Construction Applications

HIT	Cost Effectiveness*	Integrated Design	Reduced Downtime / Purchasing Timeline
LED Troffers and Controls	✓	✓	✓
EMIS	✓	✓	✓
Attachments		✓	
CCHPs	✓		✓
AFDD for RTUs and AHUs		✓	✓
Advanced Supermarket Refrigeration Systems	✓	✓	✓

*Cost effectiveness in this table refers to greater cost effectiveness in new construction situations rather than replacing current technologies nearing the end of their useful life in existing applications.

BTO regularly discusses HITs and other technologies with other government and building community members, many of which are focused on the high-performance and ZNE new construction market. The use and study of HITs and those technologies on the HIT Watch List, shown in Table 46, in new construction may provide valuable information to inform additional research and development in advanced technologies.

Table 46: HIT Watch List Candidates with New Construction Impact

Building End Use	Technology
HVAC	• Advanced heat pumps (including geothermal / wastewater / greywater-source heat pumps and cold climate heat pumps) • Advanced RTU • Modulating kitchen ventilation • Building integrated heat & moisture exchange heat & moisture exchange • Thermal storage, large chillers
Building Envelope	• Modified atmospheric insulation panels • Vacuum insulated panels • Dynamic tinted glass
Water Heater	• Drain-water waste heat recovery • Heat-recovery RTU for water preheating
Lighting	• Personal lighting controls
Whole Building	• Building energy/automation systems and controls • Dry-type distribution transformers (premium efficiency + right sizing)

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