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BTO Market Success Report 2015–2020

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Disclaimer

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List of Acronyms

ABC	Advanced Building Construction
AC	Air-conditioning
ADR	Automated demand response
AIA	American Institute of Architects
API	Application programming interface
ARRA	American Recovery and Reinvestment Act
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
ATLAS	Automated Tri-Lite Assembly System
BEADS	Building electric appliances, devices, and systems
BEM	Building energy modeling
BEMOSS	Building energy management open-source software
BENEFIT	Buildings Energy Efficiency Frontiers & Innovation Technologies
BIM	Building information modeling
BME	Blue Mountain Energy
BPS	Building performance simulation
BTO	Building Technologies Office
CAD	Computer-aided design
CCHP	Combined cooling, heating, and power
CO_2	Carbon dioxide
COP	Coefficient of performance
COVID-19	Coronavirus disease 2019
CPV	Concentrator photovoltaic
DC	Direct current
DER	Distributed energy resource
DIADR	Distributed Intelligent Automated Demand Response
DOE	Department of Energy
DR	Demand response

EC	Electrochromic
EER	Energy efficiency ratio
EERE	Office of Energy Efficiency and Renewable Energy
EFI	Energy Futures Initiative
EIFS	Exterior Insulation and Finish Systems
EPA	U.S. Environmental Protection Agency
EPS	Expanded polystyrene
ET	Emerging Technologies
FFMHP	Fuel-fired, multifunction heat pump
GEB	Grid-interactive efficient buildings
GHG	Greenhouse gas
GWP	Global warming potential
HAM	Heat, air, and moisture
HFC	Hydrofluorocarbon
HRI	High-refractive-index
HVAC	Heating, ventilating and air-conditioning
HVAC&R	Heating, ventilating and air-conditioning and refrigeration
IBPSA	International Building Performance Simulation Association
IEER	Integrated energy efficiency ratio
IC	Integrated concentrating
ILE	Internal light extraction
IoT	Internet of Things
ISO	Independent System Operator
IT	Information technology
LBNL	Lawrence Berkeley National Laboratory
LCD	Liquid crystal display
LED	Light-emitting diode
LEED	Leadership in Energy and Environmental Design
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer

OLED	Organic light-emitting diode
ORNL	Oak Ridge National Laboratory
PCB	Printed Circuit Board
PGHP	Packaged gas heat pump
PNNL	Pacific Northwest National Laboratory
POC	Point of contact
PV	Photovoltaic
R&D	Research and development
R2R	Roll-to-roll
RTO	Regional Transmission Organization
RTU	Rooftop air-conditioning unit
SBIR	Small Business Innovation Research program
SDK	Software development kit
SHGC	Solar heat gain coefficient
SPEED	Simulation Platform for Energy-Efficient Design
SRT	Sunlight-responsive thermochromic
SSL	Solid-state lighting
TCS	Tailored Control System
TES	Thermal energy storage
UV	Ultraviolet
VIP	Vacuum-insulated panels

Executive Summary

For over three decades, the Department of Energy's Building Technologies Office (BTO) has played a significant role in the improvement of U.S. energy efficiency. It has supported technology development and deployment for a range of energy-related technologies in buildings, including energy-efficient water heaters, solid-state lighting (SSL), and energy-saving windows. Today, BTO continues to support the development and market adoption of high-efficiency, and increasingly demand-flexible, products to improve energy performance and design in the building sector and to help meet national goals to put the United States on a path to achieve net-zero greenhouse gas (GHG) emissions, economy-wide, by no later than 2050—starting with a carbon-free sector by 2035 (President Biden 2021).

Technology commercialization plays an essential role in almost every facet of the U.S. economy. It spurs private sector funding that supports innovative breakthroughs, drives growth through increased productivity and product development, increases American competitiveness, and creates domestic jobs. This report is published every five years with the latest information on successfully commercialized technologies resulting in part from BTO's research funding and partnerships. This report defines a "commercialized technology" as a process, technique, design, machine, tool, material, or software that was developed with funds provided at least in part by BTO, and that has resulted in domestic sales or is in use in the United States. This definition also applies to open-source software products developed with support from BTO, all of which are currently distributed freely but are actively used for commercial purposes.

This report highlights 28 BTO-supported, technology-oriented research and development (R&D) projects that resulted in the launch of a commercial product, focusing on identifying new technologies or commercialization updates between 2015 and 2020, where the product remained on the market as of March 2021. The report also includes a listing of the full 45 commercial products supported by BTO as well as a listing of 101 lighting components that benefited from BTO support and were commercialized and integrated into finished lighting products during the same timeframe.

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1 Overview

There are roughly 129 million households and commercial buildings in the United States (123.38 million households (EIA 2021); 5.918 million commercial buildings (EIA 2020)). Buildings are the single largest energy-consuming sector of the U.S. economy, accounting for about 40% of the nation's energy consumption (EIA 2021), including about three-quarters of electricity use (EIA *Electric Power Monthly* n.d.), and the great majority of peak electricity demand. The production and use of this energy releases 35% of the country's carbon dioxide (CO_2) emissions (EIA 2021), which underscores the importance of buildings to address climate change and put the United States on a path to achieve net-zero greenhouse gas (GHG) emissions, economy-wide, by no later than 2050—starting with a carbon-free sector by 2035 (President Biden 2021).

As Americans use this energy—spending over $400 billion annually to heat, cool, light and otherwise power their buildings[1]—some 30% or more of building energy use is wasted.[2] Suboptimal equipment performance (e.g., from aging, failing, or improperly calibrated equipment), poor building design and assembly (e.g., leaky building envelopes), "phantom" loads from electric appliances and devices (e.g., electricity consumed while the appliance or device is turned off), and wasteful occupant behaviors all contribute to energy usage that does not directly support building energy services that satisfy occupant needs. By improving building energy efficiency through the development and widespread deployment of more efficient, high performance technologies and systems, the building sector can reverse these trends substantially.

1.1 Energy Efficiency is a Potent Solution for Many Energy Challenges

Energy, and especially electricity, is essential to modern economies. The demand for energy declined amid the most disruptive period of the coronavirus (COVID-19) pandemic, but energy demand is resurgent once again in the United States (EIA 2021). Energy efficiency—the use of less energy to perform the same function—keeps the growth of energy consumption from spiraling upwards. Energy is often cheaper to save than it is to produce, making energy efficiency one of the most cost-effective means to meet society's growing energy needs (Goldman, et al. 2020).

When energy efficiency is included in a clean energy portfolio, it can provide multiple additional benefits. For example, one analysis of an "optimal" clean energy portfolio with wind, solar, and energy storage resources found that energy efficiency measures delivered 23% of the portfolio's

[1] Calculated from two sources: EIA, "Natural Gas," EIA website, accessed March 2021, https://www.eia.gov/dnav/ng/ng_sum_lsum_dcu_nus_a.htm; EIA, "Electric Power Monthly: Table 5.1. Sales of Electricity to Ultimate Customers," EIA website, accessed March 2021, https://www.eia.gov/electricity/monthly/.

[2] There is no universally accepted concept of energy waste, nor has it been rigorously defined in the literature. BTO defines energy waste as energy usage that does not directly support building energy services that satisfy occupant expectations. In 2010, EPA estimated that 30% of the energy consumed in commercial buildings is wasted (EPA n.d.). BTO contributed analysis to the 2015 Quadrennial Technology Review that showed that replacing existing equipment in buildings with Energy Star technologies could result in 21%–30% energy savings depending on building type (Building Technologies Office 2015). Currently, BTO's internal analysis shows that 27% of energy consumed in residential buildings is wasted.

grid reliability needs and 39% of its electricity supply at a cost that accounts for just 16% of the portfolio's total budget (E4TheFuture 2020). An additional benefit of energy efficiency is that it can be deployed anywhere, regardless of geography or regional energy resource mixes. Furthermore, energy efficiency (as a form of demand-side management) is increasingly tied to heightened demand flexibility. By helping end users shift the time of consumption, demand flexibility provides significant savings in peak demand, better integration of variable renewables, an inexpensive variant of energy storage, greater grid reliability, and many other synergies and benefits.[3]

The economic value of energy efficiency can be measured in other ways, too. Energy efficiency has historically been cited for creating local jobs that cannot easily be outsourced as well; from 2017 to 2019, energy efficiency jobs grew twice as fast as the national rate (E4TheFuture 2020), reaching nearly 2.4 million workers by the end of 2019 (National Association of State Energy Officials [NASEO] and Energy Futures Initiative [EFI] 2020). When the COVID-19 pandemic hit the United States in 2020, the energy efficiency sector lost approximately 13% of its workforce in six months, representing about 70% of all job losses in the clean energy sector.[4] However, from 2017 to 2019, the economy added over 80,000 energy efficiency jobs annually on average,[5] which bodes well for the recovery of America's energy efficiency workforce.

1.2 How the Department of Energy Improves Building Performance

Energy efficiency jobs are often high-skilled and well-paying. Entry level wages in all sectors of energy efficiency jobs exceed the national average (E4TheFuture 2020). The Department of Energy (DOE) supports these jobs through its research and development (R&D) activities and the ensuing demonstration and deployment-focused projects. The Building Technologies Office (BTO) within the DOE's Office of Energy Efficiency and Renewable Energy (EERE) leads an expansive network of national laboratories and partners with industry, small business, non-profits, and university partners to drive the development and deployment of cost-effective, energy-saving solutions for U.S. buildings.

BTO's mission is to develop, demonstrate, and accelerate the adoption of these solutions—technologies, techniques, tools, and services—that enable high performing, energy-efficient, and

[3] BTO's Grid-interactive Efficient Buildings (GEB) Initiative is the nexus of DOE's demand flexibility research. BTO's GEB Fact Sheet introduces the core definitions, concepts, and benefits of grid-interactive efficient buildings. Its Technical Reports identify and evaluate the most promising emerging, state-of-the-art building technologies that hold significant potential to provide grid services. The GEB Roadmap quantifies the national potential of demand flexibility and makes 14 actionable recommendations to overcome barriers that currently inhibit the greater adoption and national deployment of GEBs.

[4] Over 320,000 energy efficiency jobs were lost in 2020 (as of October), a roughly 13% decline among the nation's energy efficiency workforce that began in March 2020 (E2, E4TheFuture, and American Council on Renewable Energy [ACORE] 2021).

[5] Employment figures from the past four U.S. Energy and Employment Reports (2020: 54,000 jobs, 2019: 76,000 jobs, 2018: 67,000 jobs, and 2017: 133,000 jobs) demonstrate that an average of 82,500 jobs have been added to the economy in recent years (NASEO and EFI n.d.; NASEO and EFI 2019; NASEO and EFI 2018; DOE and BW Research Partnership 2017).

demand-flexible residential and commercial buildings in both the new and existing buildings markets, residential and commercial alike. Buildings with these characteristics need less energy and use what's needed more wisely, directly supporting the strategic priority to reduce the carbon footprint of U.S. buildings.

BTO spurs the development of building technologies through its programs by enabling collaborative public and private sector research efforts to accelerate the pace of technological innovations that reduce costs and improve the performance of high-impact, energy-saving technologies. As these technologies mature, BTO demonstrates their potential by field-validating their operational performance in new and existing buildings. This reveals how new technology integrates with traditional building technologies and systems to fine-tune its potential application, prototype potential products, and pilot its production and manufacture.

BTO's technology-to-market activities work to accelerate innovative R&D concepts to address barriers on the path to commercial viability and market success. Barriers to market adoption include limited information about the technology's performance and associated value, perceived comfort or services issues, prohibitive upfront capital costs, or complex installation requirements. BTO executes strategic interventions in targeted residential and commercial buildings markets to overcome these barriers and drive uptake of technologies that BTO and its private sector partners identify as having high-impact potential.

BTO pursues a variety of activities that stimulate and accelerate this demand, including the development of certification programs and workforce training opportunities. BTO also provides technical assistance, develops and promulgates best-practices to ensure proper installations, creates design and decision tools for consumers to make informed purchasing decisions, and communicates the value and performance capabilities of novel and existing technologies.

On the tail-end of BTO's market transformation strategy, once technologies are successfully deployed and adopted by the marketplace, BTO uses its regulatory authority to establish minimum efficiency appliance and building equipment standards that set the floor for energy performance. Additionally, BTO provides technical assistance and training to support the development and adoption of model building energy codes. Together, these market signals set high performance benchmarks that incentivize further technological innovation and ultimately lock in lasting energy savings for all.

1.3 How BTO Measures its Progress

As a part of evaluating the effectiveness of BTO's strategy, BTO identifies and catalogues commercialized products and market successes roughly every five years in a formal report, as well as developing interim success stories and news articles as appropriate. The first iteration of this report, published in 2012 and entitled *Buildings R&D Breakthroughs: Technologies and Products Supported by the Building Technologies Program*, identified 20 commercially available products in building controls, lighting, windows, building envelope, water heating, heating, ventilating and air-conditioning (HVAC), and refrigeration (HVAC&R) that had received BTO

funding from 2005 to 2011. The next edition, *R&D to Market Success: BTO-Supported Technologies Commercialized from 2010–2015*, identified 27 BTO-supported, technology-oriented R&D projects that resulted in the launch of a commercial product in that period, as well as 112 lighting components that benefited from BTO support and were commercialized and integrated into finished lighting products in that timeframe.

This report showcases commercial products that received BTO funding and entered the market, focusing primarily on the time period between 2015 and 2020 after receiving BTO support. *Technologies and Innovations Enabled by the U.S. Department of Energy Building Technologies Office 2015–2020* highlights products available on the market as of April 2021, either for purchase or through an open-source download or license. This report is part of BTO's ongoing effort to identify, track, and report on commercialized technologies it supported, which serves as one indicator of success from government investment in the sector. The report describes BTO's current approach to tracking commercialized products and highlights select components and technologies that are available on the market as of 2021, along with their applications and benefits.

For decades, DOE has been funding R&D of building technologies, many of which can still be seen in the market today. For example, BTO's early-stage research contributed to light-emitting diode (LED) costs falling nearly 90% within a decade,[6] and now LEDs can be found in nearly one-third[7] of all general-illumination applications, saving Americans $14.7 billion every year and reducing electricity use in buildings by 5% (DOE 2020).

1.4 Emerging Technologies Program

The commercialized products described in this report were originally supported through R&D under BTO's Emerging Technologies (ET) program. This program advances BTO's mission to support R&D, validation, and integration of affordable, energy-saving technologies, strategies, analytical tools, and information services. ET focuses on improving energy efficiency across seven major technology areas: heating, ventilating and air-conditioning and refrigeration (HVAC&R) and water heating; windows; opaque building envelopes; lighting; sensors and controls; building electric appliances, devices, and systems (BEADS); and building energy modeling (BEM). These technology focus areas also align with BTO's R&D on its office-wide Grid-interactive Efficient Buildings (GEB) Initiative and its office-wide Advanced Building Construction (ABC) Initiative.

[6] This statement is a conservative round-down of this finding: "LEDs are 94% cheaper than they were in 2008." Considering this statistic is from 2016, and costs have only come down further, the 90% threshold remains accurate (DOE 2016).

[7] From 2016 to 2018, installations of LED products have increased in all applications, roughly doubling to 2,325 million units or 30.0% of all general illumination lighting (DOE 2020).

1.4.1 HVAC&R and Water Heating

Space conditioning and water heating account for over 40% of primary energy consumption in buildings in the United States and are major sources of carbon emissions. BTO pursues innovations and advancements in HVAC systems (heat pumps and water heaters); their constituent enabling technologies (heat exchangers, thermoelectric systems, separate sensible and latent systems for HVAC, non-vapor compression technologies, and grid-interactive controls); low global warming potential (GWP) refrigerants; and other household appliances (clothes dryers and cooking equipment).

Analysis suggests that heat pumps alone have the technical potential to save up to 50% of the energy used by conventional HVAC in residential buildings. Commercial refrigeration systems have leak rates up to 25%, contributing to GHG emissions. Replacing them with lower GWP refrigerants and reducing leak rates can significantly reduce these emissions. BTO's Initiative for Better Energy, Emissions, and Equity (E3 Initiative) focuses on advancing the R&D and national deployment of clean heating and cooling systems that include heat pumps, advanced water heaters, low-to-no global warming potential refrigerants, and smarter HVAC diagnostic tools in residential and commercial buildings. This initiative also is home to DOE's Residential Cold Climate Heat Pump Challenge, which aims to develop new technology specifications for high performance cold climate heat pumps, demonstrating its performance in the field, and launching pilot programs with utilities to identify and alleviate installation challenges.

BTO also pursues non-vapor compression technologies, which have the potential to replace or be integrated with conventional HVAC systems to reduce energy consumption by up to 50% and have low-to-zero GWP (BTO n.d. a). Heat exchangers are used not only in air-conditioning (AC), heating, water heating, and refrigeration but also in nearly every application that generates waste heat, a major cross-cutting research opportunity.

1.4.2 Windows

Windows are a key element of a building envelope, comprised of transparent and opaque materials that serve as the primary barrier between the indoor and outdoor environments. Windows offer occupant comfort through natural lighting, ventilation, and visual comfort, but currently require increased HVAC energy consumption to achieve thermal comfort. Windows are responsible for about 10% of energy use in buildings and influence end uses that comprise over 40% of building energy use (BTO n.d. b). BTO prioritizes the R&D of novel energy-efficient window technologies and systems that can convert windows from being the most energy intensive energy loss in buildings to energy providers. Research areas of interest are high-caliber insulated glass units; high performance frames; dynamic facades, daylighting and glazing; high performance windows; visible light reduction; and technology integration and implementation.

1.4.3 Opaque Building Envelope and Thermal Energy Storage

The opaque envelope affects 25% of building energy use, or 10% of total U.S. primary energy use (BTO 2020a). In order to achieve ambitious energy-saving targets, reduce total building

energy use, maximize energy savings from new HVAC systems, enable load shaping through pre-cooling and pre-heating, and take full advantage of intermittent beneficial outdoor conditions, it is critical to improve the energy performance of the opaque envelope. Retrofitting existing buildings can be leveraged to realize the energy savings potential of the opaque envelope, considering nearly 85% of residential and 55% of commercial buildings that exist today will still exist in 2050 (BTO 2020a). Although energy savings is important, the building's opaque envelope is also instrumental in maintaining occupant comfort, health, and well-being. BTO focuses on six technology areas in windows: ultra-high R/inch insulation materials; envelope diagnostic technologies; advanced modeling tools; envelope retrofit technologies; tunable heat transport materials; and thermal energy storage (TES) systems.

1.4.4 Lighting

In 2017, lighting accounted for 16% of the total electricity consumed in the United States (DOE Office of Energy Efficiency and Renewable Energy 2019). BTO fosters U.S. scientific capabilities, leverages private funds, provides internationally trusted information, and drives innovation to create efficient and flexible lighting that supports health, productivity, and well-being. Research areas of focus include platform technology R&D to lower barriers to adoption, decrease performance tradeoffs, and improve lighting application efficiency through advances in materials, components, device structures, product integration, and manufacturing technology. Moreover, integration and validation studies evaluate advanced lighting solutions and design strategies in real settings, and lighting science research informs productivity benefits and lighting application efficiency and improves our understanding of how best to apply new capabilities enabled by LED lighting.

BTO's lighting strategy is outlined in the 2022 Solid-State Lighting R&D Opportunities report, which examines the many critical opportunities that exist to positively affect energy savings, GHG emissions, human well-being, and the economy through research and development of LED-based solid-state lighting (SSL). Additionally, BTO's 2022 DOE SSL Manufacturing Status & Opportunities report examines high-priority opportunities to develop manufacturing technologies that will benefit energy-saving SSL while also supporting an increased role in the global marketplace for U.S. manufacturing of lighting products.

1.4.5 Building Controls

BTO is dedicated to developing and validating supervisory building energy management systems for residential and commercial buildings. It aims to accelerate the transition from simple, reactive, and customized controls to autonomous and interoperable solutions, adaptive to occupant and grid needs. The portfolio contributes to the goal of economic occupant comfort and zero-carbon emissions using control theory and artificial intelligence built on a foundation of cybersecurity and interoperability.

1.4.6 Building Energy Modeling (BEM)

BEM—physics-based simulation of building energy use—is a multipurpose tool for building energy efficiency. BEM informs the integrated design of envelopes, lighting systems, and HVAC

systems for high performance buildings. It supports the development of new codes and energy efficiency programs, subsequent compliance with those codes, and implementation of those programs. There is recent interest in using BEM as part of a digital twin to support building operations. BTO's BEM sub-program focuses on the development of open-source state-of-the-art BEM engines and platforms, specifically the EnergyPlus™ BEM engine, the Spawn™ BEM-controls engine, and the OpenStudio™ software development kit (SDK), which facilitates the integration of EnergyPlus and Spawn into both public and commercial applications and services. Direct participation in a technology market is an unusual role for BTO, but in the BEM space, it is one that DOE has assumed since before its ascension to a cabinet-level department, and the BEM industry has grown with and around this model. The presence of federally-funded open-source software also provides a firm basis for energy efficiency codes and financial-incentive programs. In addition to software, BTO supports testing and validation for all BEM software, standards that both apply to and leverage BEM, interoperability, BEM training and education, and research.

1.4.7 Grid-Interactive Efficient Buildings (GEB)

BTO's GEB Initiative is leading research to develop and integrate solutions that help buildings become smarter about the amount and timing of energy use and their contributions to grid performance, renewables, and DERs integration. When building equipment and systems are enabled to coordinate within—and across—buildings, they can more efficiently meet the needs of both owners and occupants while simultaneously interacting with other buildings and the electric power grid to facilitate the integration of renewable generation and electric vehicles charging and increased electrification. In order to realize this vision, BTO is taking a holistic approach that examines key energy-consuming building technologies and building-integrated distributed energy resources (DERs) (detailed in the other sections of this report) with significant potential to provide grid services and focuses on making equipment more intelligent through development of next-generation sensors, controls, connectivity, and communication. Research areas of interest include lower-cost advanced equipment control capabilities, whole-building integration of building energy systems and DERs in order to fully optimize GEB potential, improved interoperability and integration, and measurement and verification improvements.

1.4.8 Building Electric Appliances, Devices, and Systems (BEADS)

BTO's BEADS work is dedicated to the use of electricity in residential and commercial buildings beyond core technology areas. Portfolio activities focus on electric appliances, plug loads, and other miscellaneous electric loads; the sensors and building infrastructure these devices interface with; as well as system-level optimization for efficiency and intelligence across electric end uses. BTO is pursuing a variety of topics for analysis, R&D, and validation, including device power management, power conversion, distributed direct current (DC) power, load disaggregation, smart electrical panels and breakers, edge-intelligence, and edge-storage.

1.4.9 Advanced Building Construction (ABC)

As modular construction and pre-fabrication are becoming more widely used in many parts of the world, and the need for affordable housing is continuing to grow, the time is ripe for reinventing the U.S. construction industry. BTO's ABC initiative integrates energy efficiency solutions into highly productive U.S. construction practices for new buildings and retrofits. The ABC Initiative is developing building technologies that can be deployed quickly with minimal on-site construction time, are affordable and appealing to the market, and leverage related efforts to increase the productivity of the construction industry. In addition to funding research on technologies, software, and digitization, the ABC Initiative coordinates key building sector stakeholders to tackle related challenges, including workforce training, business models, demand growth, and service delivery.

The commercialized products featured in this report and organized by technology area are not an exhaustive list of every BTO-supported project that had commercial success within the study period. Rather, the following products are a selected subset of notable market success stories.

1.5 Technology Tracking Approach

The investigation described in this report identified and documented the R&D innovations and technologies that resulted from DOE support through BTO funding. Pacific Northwest National Laboratory (PNNL) previously performed technology tracking for BTO, covering its R&D portfolio in the timeframe 2005–2015, which resulted in two published reports ((BTO 2012); (BTO 2017)).

BTO requested that PNNL investigate its R&D portfolio to determine if there were updates to previously commercialized technologies or if selected projects funded between 2015 and 2020 had resulted in new commercialized products. This report summarizes the data and technology data collected for BTO by PNNL's technology tracking in fiscal year (FY) 2021.

The goal of technology tracking is to discover which R&D projects or technologies will result in a commercialized or near market-ready technology (within three to five years). PNNL began the FY 2021 tracking effort by compiling a list of active or recently completed projects from the BTO annual peer reviews 2015–2020; added to this list were technologies previously investigated by PNNL for the 2012 and 2017 reports. The resulting list was then sent back for review by BTO staff and finalized for outreach to principal investigators or other points of contact (POC).

Each R&D POC feedback was solicited by email and telephone. The POC provided input for a standard data template comprised of metrics about the technology, market, and the benefits from using the technology. In addition, data was collected from peer-reviewed articles, DOE reports, and company/organization websites. Technologies were divided into four categories:

- **Commercial Technology**: Invention or intellectual property developed into a technology (i.e., hardware, process, technique, design, machine, tool, material, or software) that enters

the domestic market as "first sale," "in use in a production application," or "sale of a commercial software license." For BTO's report, this included open-source software.

- **Emerging Technology**: Technology estimated to have a time-to-market of 3 years or less, as judged by the project's principal investigators and technology developers.
- **Potential Technology:**
  - Technology is 3–5 years from commercialization
  - Technology is being evaluated for the first time and no commercialization data is available.
- **Archived Technology**: Technology has either been tracked for 10 years, is no longer in use, or is not available for sale. Technologies that are archived can also be classified as "archived emerging" if the product did not go to market and no further efforts for commercialization are anticipated by the POC.

1.6 Findings from Technology Tracking

The FY 2021 technology tracking list contained 252 projects and technologies to be investigated by contacting the appropriate POC for the organization performing the research (Table 1). In addition to this tracking effort, this report is supplemented by the BTO Lighting program's list of internally maintained commercialized components and technologies (Appendix A) and technology articles.

The following tables show the total number of technologies for each status and the new technologies discovered during the FY 2021 tracking effort. Since the previous tracking effort, there have been 101 new technologies and 18 new commercial technologies developed from BTO funding (Table 2). There were 64 projects/technologies where PNNL was not able to contact the POC and obtain a technology status update; the last known technology status for these technologies is shown in Table 3.

PNNL found 30 commercialized technologies in the most recent tracking effort, alongside 11 commercialized technologies from previous tracking efforts that did not respond in the FY 21 effort, for a total of 41 commercialized technologies. The tracking effort also found that 4 commercial technologies are no longer available, and that development stopped on 13 emerging technologies. The remaining 86 technologies tracked did not change status (e.g., from emerging to commercial, from potential to emerging) compared to previous tracking efforts based on FY 2021 POC response.

Table 1. Total Technology Counts for FY2021

Technology Status	Count
Commercial	30
Emerging (< 3 years to market)	67
Potential (3–5 years to market)	35
Stopped/Ended (no technology developed)	39
Archive Commercial (technology no longer available)	4
Archive Emerging (technology did not go to market)	13
TBD (No response from point of contact)	64
TOTAL	**252**

Table 2. Total New Technology Counts for FY2021

New Technology Status	Count
Commercial	18
Emerging (< 3 years to market)	54
Potential (3–5 years to market)	29
TOTAL	**101**

Table 3. Technology/Projects not Updated in FY2021

New Technology Status TBD	Count
Commercial	11
Emerging (< 3 years to market)	12
Potential (3–5 years to market)	14
New project tracked in FY2021	27
TOTAL	**64**

1.7 Summary of Commercialized Products

Through FY2021 tracking, BTO R&D funding has resulted in a total of 252 technologies—41 are available commercially or in use, 79 technologies are expected to be commercialized or in use within 3 years, and 49 technologies are expected to be market-ready or in use in 3–5 years.

The majority of BTO technology development is in HVAC&R, followed closely by windows, building envelope, and building controls technologies. There are several technologies for building systems modeling and water heating. The rest of the report contains short summaries of each of the current commercial or in use technologies investigated by PNNL's technology tracking effort in FY 2021.

It should be noted that the figures for lighting products do not include the 101 component technologies commercialized from 2010 to 2020 that benefited from BTO support; they were excluded from individual analysis as each component is installed across many individual products. Thus, the lighting products represented in the four technologies listed below are representative of the types of results enabled by BTO funding within the SSL sub-program. A full list of those component technologies can be found in Appendix A.

Technologies highlighted from the BEM sub-program are open-source products developed with BTO support. Product developers are free to take these resources and incorporate them into private tools and derivative products without notifying the government. While several examples of their uptake by private actors have been noted in the one-page summaries, the list is not intended to be exhaustive. BTO's open-source tools have been highlighted to show the impact of directly supported technologies on the market, similar to the products from BTO's other technology areas.

Each of these 45 commercially available technologies is summarized below in Table 4, which includes 4 lighting technology profiles developed outside of the PNNL tracking effort. Further details about each technology, including its applications and benefits, can be found in a one-page profile of select technologies, denoted with an asterisk, in the subsequent sections.

Table 4. 45 BTO-Supported Commercially Available Technologies (2015–2020, including technologies previously tracked)

Project*	Organization	Year Commercialized
HVAC&R and Water Heating		
HVAC&R		
Advansor: High-Efficiency, Low-Emission Refrigeration System*	Hillphoenix Inc.	2014
Everest® Polyolesters: Next-Generation Refrigeration Lubricants	Chemtura Inc.	2013
Fuel-Fired, Multifunction Heat Pump	Oak Ridge National Laboratory	2016
Hydrogen/Metal Hydride Based Heat Pump System for Large HVAC Applications Utilizing an Ionic Liquid Desiccant Subsystem	Xergy	2019
Modeling Tools for Flammability Ranking of Low GWP Refrigerant Blends	National Institute of Standards and Technology	2018

Project*	Organization	Year Commercialized
Next Generation Rooftop Unit*	Trane	2018
NextAire™ Packaged Gas Heat Pump*	IntelliChoice Energy	2010
Preserva® Advanced Sequential Dual Evaporator for Refrigerators	Whirlpool Corporation	2013
Quiet Climate 2: Efficient Heat Pump for Classrooms	Bard Manufacturing Company Inc.	2008
QwikSEER+® and QwikSwap®: Energy Saving HVAC Control	Mainstream Engineering Corporation	2015, 2016
Solstice® N40: A Low Global Warming Refrigerant*	Honeywell	2014
Trilogy® 45 Q-Mode® (QE) Ground-Source Integrated Heat Pump	ClimateMaster, Inc	2012
Wireless Remote Monitoring System for Residential Air Conditioners and Heat Pumps*	Mainstream Engineering Corporation	2014
Water Heating		
Smart Energy Load Control Module: CEA 2045 Compliant Wireless Controller for Water Heaters	Emerson Electric Co	2013
Market Optimized Residential Condensing Gas Water Heater*	A.O. Smith Corporation	2006
Windows		
Automated Tri-Lite Assembly System (ATLAS™): An Energy-Efficient Triple IG Window Manufacturing System*	GED Integrated Solutions Inc.	2011
Energy-Control Low-e Retrofit Window Film*	Eastman Chemical Company	2011, 2020
Low-Cost R10/High Solar Heat Gain Coefficient (SHGC) Heat Mirror® Window Development*	Southwall Insulating Glass LLC	2013
OptiQ™: An Advanced Commercial Window Technology*	Kawaneer North America	2011, 2014, 2015
SageGlass®: Electrochromic Windows Advanced Processing Technology*	SAGE Electrochromics Inc.	2007
Suntuitive™: Sunlight-Responsive Thermochromic Window Systems	Pleotint LLC	2011
Triple Glazing with Thin Non-Structural Center Glass*	Lawrence Berkeley National Laboratory	2019
View Smart Windows: Solid-State Dynamic Glass a Large Opportunity for Sustainable Buildings*	View Inc.	2007

Project*	Organization	Year Commercialized
Opaque Building Envelope and Thermal Energy Storage		
Precast Concrete Molds Using 3D Printing Technology*	Oak Ridge National Laboratory	2019
Dryvit Outsulation: Energy-Efficient Exterior Insulation and Finish Systems (EIFS) Wall Systems	Dryvit Systems Inc.	2017
LIQUIDARMOR™: Advanced Energy-Saving Flashing and Sealant for Buildings	Dupont	2014
ThermaDeck®: An Insulated and Ventilated Roof System	Billy Ellis Roofing LLC	2012
Integrated Concentrating (IC) Solar Envelope: Energy-Efficient Facades for Green Buildings*	HeliOptix LLC	2019/2020
Air Barriers 3M 3015*	3M	2015, 2021
IC Solar Array: Energy-Efficient Facades for Green Buildings	HeliOptix LLC	2015
Lighting		
Finelite FineTune® Tailored Control System (TCS)*	Finelite Inc.	2019
Lucent Optics Ultra-Thin Flexible LED Lighting Panels*	Lucent Optics	2020
Lumileds LUXEON® LEDs*	Lumileds	2017
OLEDWorks Brite 3 OLED Lighting Panels*	OLEDWorks	2018
Pixelligent Light Extraction Materials*	Pixelligent	2018
Building Controls		
Building Energy Management Open-Source Software Development (BEMOSS)*	Virginia Polytechnic Institute and State University	2016
Energy-Harvesting, Self-calibrating Wireless Sensors for Improving Energy Efficiency in Buildings*	Molex	2019
OpenADR Client: Distributed Intelligent Automated Demand Response (DIADR) Building Management System	Siemens Corporation	2011
Predictive Control Harnesses Building Thermal Mass as High Performance Energy Storage	QCoefficient Inc.	2012
Building Energy Modeling		

Project*	Organization	Year Commercialized
EnergyPlus Whole Building Energy Modeling Engine*	National Renewable Energy Laboratory	2012[8]
OpenStudio*	National Renewable Energy Laboratory	2013[9]
EcoStruxure IT Advisor CFD – Data Center Toolkit*	Schneider Electric R&D Center	2020
Ladybug Tools: Computer Aided Design (CAD)-Integrated Web-Based Building Performance Simulation Platform*	Ladybug Tools LLC	2021
VOLTTRON™: Controller for Energy Systems*	Pacific Northwest National Laboratory	2018
PCM Simulator for Energy Systems	National Renewable Energy Laboratory	2017[10]

[8] The year this open-source technology was commercialized refers to the year when the technology was released as a non-beta commercial grade product—whereby the product is no longer in the development stages and can be downloaded, installed, and/or modified to meet different user needs
[9] Ibid
[10] Ibid

2 HVAC&R and Water Heating

HVAC systems and water heating equipment consumed approximately 20 quads of primary energy in the United States in 2020, representing 47% of total energy use in buildings (EIA 2021). DOE has invested in R&D of energy-efficient HVAC and water heating technologies and alternative refrigerants since the 1980s, and BTO leads efforts to develop next generation technologies with advanced capabilities and clear paths toward commercialization. The HVAC&R and Water Heating sub-program follows a two-pronged strategy for R&D of new technologies. First, the sub-program aims to accelerate the development of near-term technologies with the potential to save significant amounts of energy, reduce emissions, and explore related cost reduction activities to help bend the cost curve. Second, the sub-program is exploring entirely new approaches for the development of next-generation technologies that can potentially "leapfrog" existing technologies.

2.1 HVAC&R

HVAC systems today represent the largest energy end use in buildings, accounting for nearly 15 quads of primary energy use annually, or about 38% of all energy consumed in U.S. residential and commercial buildings each year (EIA 2021). Furthermore, analysis suggests AC energy use will grow faster than any other building sector end use application through 2050. Although energy use for space heating is expected to decline, higher anticipated residential and commercial energy consumption for AC results from projected population shifts from colder to warmer parts of the United States (EIA 2020).

In 2019, purchased electricity accounted for 94% of delivered energy for AC across the buildings sector. Although associated electricity generation is a significant driver of emissions from HVAC and commercial refrigeration operations, emissions from hydrofluorocarbon (HFC) refrigerants have a large direct global warming impact. To address this, BTO continues its research and partnering efforts to transition HVAC and commercial refrigeration systems away from HFCs without sacrificing performance and efficiency. Looking ahead to 2050, over 70% of households are projected to be single-family homes that typically have more air-conditioned floorspace than multifamily or mobile homes. In addition, office buildings, which consume more energy for AC than any other building type, are estimated to consume 25% of U.S. commercial sector AC in 2050 (EIA 2020). Considering that office space represents only 16% of the number of commercial buildings and 17% of total commercial building floorspace in the United States (in square feet) (EIA 2020), these estimates highlight the critical role that advanced HVAC technologies can play in reducing energy use and emissions from the buildings sector.

The sub-program focuses on three timeframes: short-, mid-, and long-term. In the short-term, the sub-program focuses on energy savings using today's existing technologies by developing and evaluating alternative refrigerants. Mid-term priorities target the energy savings from using advanced technologies and systems that are designed for next-generation refrigerants. Long-term

objectives aim to realize energy savings from next-generation technologies by developing non-vapor compression systems that use zero GWP refrigerants.

Technology focus areas include cold climate heat pumps, low-GWP heat pump water heaters, low-GWP heat pumps, thermoelectric systems, separate sensible and latent systems for HVAC, low-GWP supermarket refrigeration systems, heat exchangers, and grid-interactive HVAC and water heaters.

2.2 Water Heating

Water heaters provide buildings with hot water almost instantaneously, either with storage or tankless units. Water heating accounts for 9% of primary energy use in buildings, though roughly 80% of this energy is consumed in the residential sector (EIA 2021). The laundry, bathing, dishwashing, and cleaning that occurs in a home adds up, and typically is the second largest energy-consuming activity in the home, accounting for about 14% of energy used after space heating and cooling (EIA 2021).

To encourage adoption and market penetration of advanced water heating technologies, BTO funds R&D to reduce the cost while improving energy efficiency. Overall, a cost-effective, energy-efficient water heating system can minimize customer energy bills while maintaining adequate hot water in the home or commercial building.

One BTO research priority area is integrated heat pump technologies, where heat from one heat pump-driven process (e.g., space conditioning) can be used as the source of energy for another (e.g., water heating). Additional BTO water heating R&D activities are focused on developing heat pump water heaters with low-GWP refrigerants that operate at lower voltage.

2.3 Next Generation Rooftop Unit

More than half of the building space in U.S. commercial buildings is cooled by rooftop AC units (RTUs). Existing RTUs consume more than 1.3% of the total U.S. energy annually (1.0 Quad source energy). Advances in energy efficiency with HVAC technology have resulted in new equipment that can reach higher energy efficiency standards, making many current units inefficient by comparison. These technologies can be incorporated in RTUs to meet the new target Integrated Energy Efficiency Ratio (IEER) standards, enabling significant reductions in HVAC energy consumption.

Oak Ridge National Laboratory (ORNL), with assistance from BTO and industry partners Trane Company, Emerson, and Ebm-papst, has developed an RTU with various improvements to its existing design to achieve high energy efficiencies. Starting from a baseline unit provided by Trane Company, with a rated cooling capacity of 13 tons and 17.9 IEER, improvements in energy efficiency were made by exchanging multiple component parts.

A combination of two, 2-stage compressors and a single-speed compressor made by Emerson were used to reconfigure the vapor compression system. This trio converter set provides seventeen capacity levels without using inverter-driven compressors, making it a cost-effective and energy-efficient option. The indoor blower was also replaced with three parallel high-efficiency backward-curved fans made by Ebm-papst, which improved indoor air flow distribution, heat transfer, and reduced the indoor blower power consumption by 30%. Additionally, a submerged subcooler was added to recover free cooling capacity from the condensate water without adding power consumption. Lastly, R-452B, a low GWP refrigerant, was tested as a drop-in replacement for the existing refrigerant, R-410A, which resulted in a 5% increase in efficiency over R-410A. Due to the slightly flammable properties of R-452B, modifications to existing refrigeration system safety standards and building codes are needed before it can be used in RTU systems.

Technology History:

ORNL's Next Generation RTU began development in 2011 in partnership with Trane Company, which constructed lab breadboard and prototype units. Lab breadboard units were tested at ORNL to verify key performance targets and build energy simulations used to develop a series of 10-to-20-ton capacity prototype RTUs. The refrigerant tests of R-452B were performed in 2015. In 2016, a field prototype unit was tested and succeeded in operating during the cooling season without reliability issues, with a seasonal Energy Efficiency Ratio of 20.8. After the successful field test, Trane Company began pursuing opportunities to introduce high-efficiency RTUs that implement the features developed. Currently, the concept of trio compressors for high-efficiency RTUs has been used in a variety of products on the commercial market.

Applications:

- Production of component technologies (trio compressors, backward-curved indoor blowers, submerged subcoolers, and drop-in low GWP refrigerant replacement) for installation in existing RTU products

Capabilities:

- Construction of an RTU with a measured IEER greater than 22.0 with a cooling capacity range between 10–20 tons
- Production of low-cost capacity modulation-trio compressors that provide 17 capacity levels without using inverter-driven compressors
- Production of three parallel backward-curved blowers for improved indoor air flow distribution and heat transfer while reducing indoor blower power by 30%

Benefits:

- Predicted reduction of HVAC energy consumption in commercial buildings by as much as 50%
- Potential energy cost savings of more than $1 billion per year within the United States

Learn More:

- BTO Project Page
- 2017 Peer Review

Contact

Oak Ridge National Laboratory
1 Bethel Valley Road
Oak Ridge, TN 37830
www.ornl.gov

2.4 Advansor™: High-Efficiency, Low-Emission Refrigeration System

Hillphoenix's Parallel Rack System with Advansor™

There are approximately 37,000 supermarkets in the United States that require substantial amounts of refrigerated floor space for displays and back-room storage. Refrigeration accounts for nearly half of all U.S. supermarket energy consumption, totaling 0.68 quads of primary energy usage every year. Refrigeration systems in supermarkets require numerous piping interconnections to connect food display cases and storage rooms, which poses a problem with refrigerant leakage. On average, supermarkets leak 24% of their refrigerants, such as R-404A or R407A, which have a direct effect on GHG emissions because they are HFCs with high GWPs. Leakage also increases refrigeration system inefficiencies, thereby contributing to higher indirect GHG emissions.

With funding and assistance from BTO, ORNL and Hillphoenix Inc. developed the Advansor™ transcritical CO_2 booster system to address these issues. The Advansor™ system, which uses CO_2 as its refrigerant, reduces GHG emissions from commercial refrigeration systems by over 75%. It works by (1) lowering refrigerant usage, (2) employing improved construction techniques to reduce leak rates, and (3) utilizing a low-cost, low-GWP CO_2 refrigerant. As GHG emission regulations become more stringent, refrigerants with high GWPs will be replaced by their lower GWP alternatives. Installing a CO_2 refrigeration system would eliminate the need for system retrofits in the future in order to comply with environmental regulations.

In addition to its environmental benefits, the Advansor™ system has been verified (through testing by ORNL) to use less energy than other refrigeration systems, depending on the climate region. The Advansor™ system will allow regions with lower ambient temperatures to achieve greater energy savings than conventional HFC-based refrigeration systems. Natural refrigerant-based refrigeration systems (e.g., CO_2) have been successfully implemented in Canadian and European markets, giving U.S. manufacturers and consumers more confidence to explore these options. As of the end of 2020, there have been over 700 systems deployed.

Technology History:

Developed and tested by Hillphoenix and ORNL with assistance from Danfoss, Luvata, and SWEP, the Advansor™ refrigeration system was first commercialized in 2014. Efforts are ongoing to evaluate potential applications and develop marketing strategies as Hillphoenix continues to deploy Natural Refrigerant solutions utilizing CO_2 as a refrigerant. The Hillphoenix Advansor Transcritical Booster System was named an R&D 100 Award Finalist in 2015.

Applications:

- A low-GWP replacement for traditional commercial refrigeration systems

Capabilities:

- More efficient than conventional refrigeration systems in most climate zones in the U.S.
- Uses a natural refrigerant (CO_2) with zero ozone depletion potential and a GWP of 1

Benefits:

- Offers lower installation costs than conventional supermarket refrigeration systems
- Reduces energy consumption by 25%
- Reduces GHG emissions by 75%

Learn More:

- BTO Project Page
- BTO Success Story

Contact

Hillphoenix Inc.
2016 Gees Mill Road
Conyers, GA 30013
www.hillphoenix.com

2.5 Solstice® N40: A Low Global Warming Refrigerant Solution

Solstice N40®(R-448A) Cylinder

Thousands of supermarkets across the country operate large-scale refrigeration systems, making it one of the most energy-intensive commercial sectors. These refrigeration systems require large amounts of electricity and refrigerants to chill and freeze perishable foods. The refrigerants used by these systems are HFCs, or strong GHGs with very high GWPs. Today, the most commonly used refrigerant is R-404A. Each year, a typical supermarket refrigeration system can leak up to 1,000 pounds of R-404A, the equivalent emissions of 3.9 million pounds of CO_2. Improving efficiency and reducing the GWP refrigerants in commercial refrigeration systems will reduce harmful climate impacts to the global environment.

Solstice® N40 is a low-GWP refrigerant for commercial refrigeration systems. It provides an environmentally friendly solution to mitigate the high CO_2 equivalent emissions of conventional refrigerants. It is a non-toxic hydrofluoroolefin-based refrigerant alternative. Lab studies conducted by ORNL and Honeywell concluded that N40 could replace R-404A in existing supermarkets while providing a significant reduction in GWP and lower energy consumption. N40 is non-flammable and is compatible with typical system components used with R-404A commercial refrigeration systems, which makes it suitable for retrofit applications. Future work will focus on field evaluation of N40 in third-party commercial refrigeration systems to validate the performance benefits in the field.

Globally, Solstice N40 has been successful in a wide range of commercial refrigeration applications. Components (compressors, heat exchangers, valves, and accessories) for refrigerant systems have been qualified by various suppliers. Commercial systems of N40 are available from leading original equipment manufacturers (OEMs), such as Heatcraft, Hill Phoenix, Hussmann, Zero Zone, Krack, and Russell. Retailers, such as Whole Foods Market in the United States and Papaya Fresh Gallery in Indonesia, have adopted N40 in their supermarket refrigeration system.

Technology History:

Solstice® N40 was developed by Honeywell. The company received assistance from BTO to work with ORNL to test and evaluate the performance against the conventional R404A refrigerant. The technology was commercialized in 2014 and continues to undergo evaluation in supermarket refrigeration systems. It was named an R&D 100 Award Finalist and received the U.S. Environmental Protection Agency (EPA) Significant New Alternatives Policy Approval for new and retrofitting supermarket refrigeration systems in 2015.

Applications:

- A direct low GWP refrigerant replacement for existing R-404A systems such as commercial refrigeration systems and chillers

Capabilities:

- Achieves higher coefficient of performance (COP) (independent laboratory evaluations demonstrated 11% improved energy efficiency) compared to R-404A
- Compatible with R404A supermarket systems and maintains refrigeration capacity

Benefits:

- Non-flammable (American Society of Heating, Refrigerating and Air-Conditioning Engineers [ASHRAE] A1)
- Low GWP of 1273
- Maintains or improves refrigeration capacity using existing R404A equipment
- 65% direct emissions reduction and 67% reduction in GWP compared to R404A
- Reduces indirect emissions of supermarket systems after retrofit
- Enables phasing out hydrochlorofluorocarbons (R22) by allowing retrofit of R22 systems.

Learn More:

- BTO Success Story

Contact

Honeywell
20 Peabody Street
Buffalo, NY 14210
www.honeywell-refrigerants.com

2.6 NextAire™ Packaged Gas Heat Pump

Blue Mountain Energy's 11-ton NextAire PGHP

U.S. commercial buildings are predominantly cooled and heated using packaged RTUs, most of which rely on electric-motor-driven compressors in the refrigeration cycle. Unfortunately, these units are expensive to operate when electricity prices and demand charges are high, particularly in summer months when the demand for cooling services peak. Increased electricity demand for space cooling during peak hours also puts stress on regional electric grids by requiring the production of excess generation capacity that is underutilized during off-peak hours.

In search of an alternative source of power to operate space conditioning equipment, IntelliChoice Energy, doing business as Blue Mountain Energy (BME), with assistance from BTO and the U.S. Department of Defense, developed the NextAire 11-ton packaged gas heat pump (PGHP). The PGHP uses a natural-gas-fired engine instead of an electric motor to drive the refrigerant compression cycle, providing numerous efficiency benefits. The unit's efficiency is enhanced in heating mode by its ability to capture and use waste heat from the engine for space heating. The engine can also operate at variable speeds, so it operates efficiently below its maximum cooling capacity. Because the PGHP occupies a similar footprint to traditional electric units currently in use, it is well-suited for both new commercial construction and retrofit applications.

Widespread use of gas heat pump technology has the potential to produce large energy efficiency and resource conservation gains at the national level. According to the U.S. Energy Information Administration, more than 60% of primary energy consumed to generate the nation's electricity is lost in power plants during the conversion process. Shifting a significant fraction of commercial space conditioning to on-site natural gas would avoid these conversion losses while simultaneously offsetting large amounts of water that would otherwise be consumed for traditional electricity generation purposes. Recently, BME has supplied gas heat pump equipment to indoor urban and rural farming operations where demand for heating and cooling has increased. BME's propane fueled systems can be used where there is inadequate electricity and natural gas infrastructure.

Technology History:

NextAire was developed by IntelliChoice Energy with assistance from Southwest Gas Corporation and ORNL. The product was commercialized in 2010. The technology has received numerous awards, including the 2010 New Product Award from the National Society of Professional Engineers and a 2011 R&D 100 award for innovation in technology. Efforts are ongoing to bring down initial installation costs.

Applications:

- Low-cost, energy-efficient space conditioning for commercial buildings

Capabilities:

- Uses a natural-gas-fired engine instead of an electric motor to drive refrigerant compressors
- Provides 11 tons of cooling/heating capacity with a cooling COP of 1.1 and a heating COP of 1.4
- Quiet operation (<60dB) compared to a typical HVAC unit (>75dB)

Benefits:

- Reduces operating costs by avoiding expensive demand and time-of-use electricity charges
- Saves 0.5 gallons of water per kWh compared to similar-sized electric units consuming grid-generated energy
- Enables Leadership in Energy and Environmental Design (LEED) points for green-building certification

Learn More:

- BTO Project Page

Contact

Blue Mountain Energy
2949 W. Lakeland Blvd.
Las Vegas, NV 89032
bluemountainenergy.com

2.7 Wireless Remote Monitoring System for Residential Air Conditioners and Heat Pumps

Mainstream's Remote Monitoring System

In a typical home, an AC or heat pump system is one of the largest consumers of energy. If an AC is operating at degraded efficiency, this typically results in wasted energy, reduced system life, and a tendency for units to fail on extremely hot days. A homeowner may not be aware of the equipment problem if the air temperature in the house is still comfortable. Units that "break on the hottest day of the year" usually have been operating for some time at a reduced cooling capacity and for longer periods without cycling, but the reduced capacity only becomes apparent on the first hot day, when the unit cannot maintain the setpoint temperature.

Conventional systems capable of monitoring the "operational health" of AC units are typically expensive and only report raw sensor data that consumers cannot interpret. Therefore, new technologies are needed that are capable of analyzing a unit's performance and identifying problems, along with their likely causes, to create a warning system for homeowners so they can take preventative actions to avert AC unit failures.

With assistance from BTO through an Energy Small Business Innovation Research (SBIR) grant funded by the American Recovery and Reinvestment Act, Mainstream Engineering Corporation developed an innovative, low-cost device to detect problems and identify their causes. The remote monitoring system continuously monitors a unit to detect any maintenance needs (e.g., a clogged air filter or dirty condenser coils) and service issues (e.g., low refrigerant charge, faulty fans/blowers, or compressor short cycling) before they create system failures. Once a problem is detected, the system automatically sends a notification with problem-specific information to the homeowner and the HVAC service company that installed the unit. This information enables the service company to send a technician with the proper supplies, saving time and money by avoiding multiple trips. The homeowner or technician can log on to a secure website and investigate the unit's energy consumption, compare its current performance to previous data, and perform calculations to determine the economic feasibility of replacing the current unit with a more efficient one.

Technology History:

Mainstream Engineering Corporation commercialized the remote monitoring system technology in 2014. It is currently being field-tested with various regional commercialization partners in the HVAC&R service industry. The remote monitoring system has received five patents since 2015, and Mainstream anticipates moving forward with full commercialization nationally.

Applications:

- Automatically monitors and detects faults in residential AC systems

Capabilities:

- Diagnoses common HVAC problems that waste energy and shorten equipment life
- Transmits information on system welfare to the homeowner and repair technician via a wireless internet signal
- Records equipment operating history to allow for energy consumption analysis and comparison

Benefits:

- Prevents costly replacement of failed units by alerting homeowners to simple maintenance issues that can be fixed with minimum time and expense
- Saves energy and money by rapidly detecting and resolving problems that degrade unit efficiency (e.g., low refrigerant charge)
- Maintains or improves refrigeration capacity using existing R404A equipment

Contact

Mainstream Engineering Corporation
200 Yellow Place
Rockledge, FL 32955
www.mainstream-engr.com

2.8 Market Optimized Residential Condensing Gas Water Heater

A.O. Smith Vertex™ Product Line of Residential Gas Water Heaters (75 gal pictured)

Heating water is the third largest energy cost in the average U.S. home, leading water heater manufacturers to create new designs to increase energy efficiency and provide cost savings without sacrificing performance, satisfying the need for a cost-optimized, high-efficiency water heater. As with any industry, innovative products require large investments in engineering, design, and manufacturing processes—expenses that can lead to additional out-of-pocket costs for consumers.

With assistance from BTO, A.O. Smith Corporation created a family of state-of-the-art gas-fired water heaters that provide a long-lasting supply of hot water. The technology used readily available components and materials, minimizing development and manufacturing cost increases. In addition to the use of conventional water heater parts, a glass-lined low-carbon steel heat exchanger was also developed. The glass-lined heat exchanger material delivered significant costs savings when compared to stainless steel while simplifying manufacture and delivering strong high-efficiency performance.

A.O. Smith commercialized the technology in 2006 with the release of the Vertex™ product family. The design specifications were refined to include a larger burner to support space heating and hot water applications. The 2008 Vertex 100 added features such as onboard diagnostics and remote monitoring capabilities as well as an upgraded temperature controller with a liquid crystal display (LCD) user interface. In 2013, the Vertex residential family of gas water heaters was certified by the EPA's ENERGY STAR® program, making the Vertex the first high-efficiency tank-style water heater with more than 75,000 BTU input to be certified. In 2014, A.O. Smith released a 75-gallon Vertex with a new ignition system.

Technology History:

Vertex™ water heaters, available from A.O. Smith Corporation, were commercialized in 2006. The product family was certified as an Energy Star Product in 2013, and in 2021, A.O. Smith received an Energy Star Partner of the Year: Sustained Excellence award.

Applications:

- Can be used for residential or light commercial applications.

Capabilities:

- Achieves up to 96% thermal efficiency with an input heating rate of up to 100,000 Btu per hr.
- May be operated as part of a combination space heating/water heating system.
- Constant flow of over four gallons a minute.

Benefits:

- Installs easily using existing utility connections and can be vented using PVC pipe.
- Provides reliable performance by using a field-tested and cost-effective design.
- Produces hot water at a rate that exceeds that of a larger, standard 75-gallon unit.
- Achieves up to 30% energy savings when compared to a standard gas water heater.

Learn More:

- BTO Final Report
- Vertex Product Family

Contact

A.O. Smith Corporation
500 Tennessee Waltz Pkwy.
Ashland City, TN 37105
http://www.hotwater.com

3 Windows

Windows and window attachments have a significant influence on a building's overall energy performance. They are responsible for about 10% of energy use in buildings and influence end uses, like space heating, cooling systems, and lighting, that comprise over 40% of building energy use (BTO 2020b). They also provide an opportunity for improving building energy efficiency and occupant comfort. Advanced and novel window technologies could yield substantial energy savings while also reducing peak electricity demand on behalf of commercial and residential buildings. The components that offer the greatest opportunity for energy savings are thermal loss, variable solar control, and harvesting of daylighting (BTO n.d. b).

With input from key stakeholders, the sub-program recently developed a research and development opportunities report for windows that focuses on R&D for windows and window system technologies and will inform BTO's investments in developing the next generation of high performance, affordable, cost-competitive windows, as well as integrated daylighting and shading technologies. This report also addresses areas where DOE invests in software and design tools that translate sophisticated concepts into easy-to-use energy performance and optimization methods used by industry and other stakeholders for implementation. Today, over 90% of windows are designed using DOE software tools.

As part of the larger ET program priorities to reduce energy use intensity, the Windows sub-program focuses on advancing the development and widespread adoption of next-generation window technologies. The sub-program emphasizes technology development that will have attractive, market-ready characteristics, including acceptable payback periods and installation costs, aesthetics, durability, and sustained energy performance over the lifetime of the technology.

Next-generation window technologies R&D also can improve occupant comfort and reduce HVAC system capacities in commercial buildings. Technologies such as integrated facade and electric lighting systems have been validated to save significant energy while reducing peak electricity loads by more than 30% (BTO 2020b).

BTO's window R&D efforts focus on insulating windows, dynamic solar control, and daylighting and shading systems. R&D in these areas as well as new material discovery, novel technological approaches and applied engineering is key to addressing performance and cost challenges faced by industry to produce highly efficient, affordable windows.

3.1 Low-Cost R10/High SHGC Heat Mirror® Window Development

Southwall's Heat Mirror® concept for highly-insulating, light-weight insulating glass units

Typical insulating glass units used in buildings employ internal gas filled cavities to increase the insulating performance of the units. Adding multiple gas cavities is an effective path to further improve R-value, but it is limited by the significant weight of added glass panes and overall thickness of the insulating glass unit. Also, multiple layers of solar infrared-reflecting coatings reduce visible transmittance and the SHGC, diminishing the potential for passive solar heating desired for northern climate zones.

With assistance from the U.S Department of Energy, Southwall Technologies Inc. has demonstrated low-cost manufacturing of Heat Mirror® film insulating glass units with center-of-glass performance up to R-10 and a solar heat gain coefficient of approximately 0.50. The project was focused on developing the manufacturing process for high volume and high-speed production of thin film triple-pane single film (R5) and dual film (R10) insulating glass units.

Heat Mirror® film replaces the inner glass panes of multi-cavity insulating glass units with suspended, coated polymer films that enable multiple cavities at much lower weight and thinner overall thickness than all-glass insulating glass units.

Technology History:

Heat Mirror® film was developed by Southwall Technologies Inc. and was originally commercialized in the 1970s. The manufacturing process for constructing insulating glass units containing Heat Mirror® film has historically hindered widespread adoption of the technology.

The manufacturing-focused project described above was a technical success, offering higher production capability with reduced labor intensity; however, the economy's economic conditions at the time did not lead to a successful business venture. The equipment and process developed with DOE funding was later sold, and it enables other window companies to offer more viable, lightweight triple-pane windows.

In 2015, Eastman Chemical Company dissolved Southwall Technologies, Inc,. and the technology is available through Eastman and select licensees (Alpen High Performance Products and Helmut Hachtel GmbH).

Applications:

- Can be used to improve the building energy efficiency in northern climates by reducing glazing heat loss and enabling passive solar heating

Capabilities:

- Reduces incoming UV by 99.5%
- Achieves R-values of up to 10
- Heat mirror can be produced in automated, high-volume manufacturing lines
- High SHGC enables passive solar heating

Benefits:

- Optimizes building energy usage by reducing heat loss through glazing
- Allows more extensive use of natural daylight in building lighting

Learn More:

- Alpen High Performance Products – Heat Mirror

Contact

Eastman Chemical Company
4210 The Great Road
Fieldale, VA 24089
http://www.eastman.com/Brands/HeatMirror/

3.2 Energy-Control Low-e Retrofit Window Film

Eastman's VS20 SR CDF SpectraSelect Film

R&D to improve energy conservation with new window technologies has investigated fenestration, glazing, and glazing treatments, including active and passive window tinting. For a technology to become successful in the consumer marketplace, the cost of ownership must have a perceived value and a short payback period. Also, technologies that can be retrofitted easily and cost-effectively are desirable.

Eastman Performance Films LLC and its predecessors, with assistance from BTO (as part of the American Recovery and Reinvestment Act), developed a low emissivity (low-e) retrofit window film technology that reached an emissivity of 0.07, comparable to some low-e coatings used in sealed insulating glass units. The low-e coating was developed in such a way to minimize this iridescence, providing for a more aesthetically pleasing film.

The improvement in insulating performance from the low-e coating coupled with the film's solar-control properties result in unequalled energy savings compared to other standard solar-control and conventional low-e films. The EnerLogic 35 window film can provide for simple paybacks and returns on investment on a level comparable to other commonly used energy efficiency measures.

While Enerlogic innovated the low-e window film and it was sold for several years with numerous applications, it ended up not being market viable. However, DOE's investment helped inspire innovation across the industry, and today, several other companies are offering similar low-e window films.

Technology History:

This technology was developed by Eastman in 2011. The original product, Enerlogic® 35, was recently replaced in 2020 with the VS20/30/50 SR CDF Spectrally Selective Series films, which have improved reliability and durability but increased emissivity. Since the introduction of Eastman's energy-control retrofit window film product over ten years ago, over 2.5 million square feet have been installed. In 2019, DOE recognized Eastman's participation in the Better Plants Challenge, where they achieved a 12% manufacturing energy reduction. The Better Plants Challenge is part of DOE's Better Buildings Initiative.

Applications:

- Can be used in most existing window applications, mostly suited for single and double uncoated glass

Capabilities:

- Can be installed in a variety of existing low-e commercial or residential windows (single or dual pane and tinted or clear)
- Meets American Society for Testing and Materials (ASTM) E903 test method for solar absorptance, reflectance, and transmittance
- Spectrally-selective films reduce solar heat gain by selectively reducing near-infrared radiation more than visible light. (Light Solar Heat Gain Ratio >1.0)

Benefits:

- Reduces costs by eliminating expensive replacement of existing windows
- Improves product durability and flexibility using flexible display manufacturing techniques combined with precious-metal sputter coating
- Improves window energy efficiency using reduced emissivity film coating. Eastman architectural films typically become carbon neutral in less than 2 months of use
- Improves thermal and visual comfort, along with resiliency

Learn More:

- Spectrally Selective Window Films

Contact

Eastman Performance Films LLC
4210 The Great Road
Fieldale, VA 24089
www.eastman.com

3.3 ATLAS™: An Energy-Efficient Triple IG Window Manufacturing System

ATLAS™ Window Manufacturing System

A considerable portion of the energy consumed in commercial buildings is affected by the insulation capacity and optical properties of windows. DOE identified heat loss through windows as the largest single energy-related aspect of window performance.

Low-e glass coatings, or "glazings," and the introduction of inert gases in the space between windowpanes are two technology areas that have reduced energy losses, but opportunities remain to increase energy savings further by addressing glazing properties and the sash/frame combination. To provide customers with more affordable and efficient commercial and residential windows that can reduce their energy bills, DOE has enabled the research, design, and development of high-volume, efficient manufacturing processes that can produce high performance, energy-saving insulating glass units.

With funding from BTO, GED Integrated Solutions Inc. developed a high-volume, low-material, and low-labor-cost automated manufacturing system that produces high performance insulating glass units. GED's revolutionary ATLAS™ provides a combination of the highest quality, lowest total cost, and highest capacity manufacturing of triple-paned windows in the industry. The ATLAS™ produces a triple-pane insulating glass unit in 20 seconds, improving on conventional methods that can take two minutes or longer. ATLAS™ integrates with existing *Intercept*® lines and other spacer systems that create effective thermal barriers to reduce heat loss through windows, thereby retaining a window's insulating gas more effectively.

GED's ATLAS™ has been installed in many window manufacturing facilities. This allows GED customers the ability to produce a wide variety of insulating glass unit sizes for high thermal efficiency windows at high volumes and cost effectively.

Technology History:

This technology was developed by GED Integrated Solutions Inc. and was commercialized in 2011. PPG Industries Inc. (now Vitro), a major U.S.-based glass manufacturer and developer of advanced window technologies, assisted GED with unit design support and analytical testing and commissioned the first ATLAS™ to validate performance in an actual production environment. It was awarded "Best in Show" in September 2011 at GlassBuild America, a major glass and window industry event. Since then, many of GED's customers who manufacture triple insulating glass units, are using the technology provided by ATLAS™.

Applications:

- Currently being utilized by high- and low-volume manufacturers of insulating glass and residential windows in multiple locations

Capabilities:

- Provides seamless integration into existing equipment and flexible, schedule-driven production
- Processes units from 16″ × 14″ up to 100″ × 72″ at a rate of up to 6 IG dual units per minute
- Uses vacuum lift mechanisms to lift and suspend the product without contacting glass surfaces, which ensures the contamination-free placement and alignment of triple insulating glass units

Benefits:

- Cheapest and highest-volume method for making energy-efficient triple- and dual-insulating glass units
- Minimizes glass breakage, contamination, and damage and protects workers from injury and fatigue from handling glass using touchless assembly
- Provides capability to handle small- and large-sized units and dual- or triple-glazed insulating glass units in any order or combination while maintaining optimum levels of production

Contact

GED Integrated Solutions Inc.
31100 Diamond Parkway
Glenwillow, OH 44139
www.gedusa.com

3.4 View Smart Windows: Solid-State Dynamic Glass a Large Opportunity for Sustainable Buildings

View Electrochromic Glass in Various Tint States

In the United States, residential and commercial building HVAC systems consume 7.7 quads per year (EIA 2019). Heat gain and heat loss through windows is responsible for 25%–30% heating and cooling energy use (DOE n.d.). DOE estimates a major contribution to energy conservation could be made by eliminating HVAC energy consumption from solar loading. Dynamic, electrochromic (EC) or "smart" windows can switch between clear and tinted states to block direct sunlight and radiant heat in the summer and transmit radiant heat in the winter. Adoption of smart window technologies could significantly reduce energy use associated with HVAC and lighting.

With funding from BTO, View Inc. ("View") developed and commercialized dynamic glass based on EC technology, a multilayer coating stack applied to the inner surface of the outer pane of glass in a double-pane or triple-pane insulating glass unit. View Smart Windows can be tinted by applying a small DC voltage, allowing the glass to operate from clear to fully tinted.

View Smart Windows eliminate glare and block over twice as much solar heat as state-of-the-art, low-emissivity glass. Building occupant comfort is also improved by reducing eyestrain, headaches, and drowsiness compared to buildings with traditional blinds. Optimized natural light enhances mental and physical well-being and improves cognitive performance and productivity of occupants. In cold weather, the windows can adapt to allow the sun's rays to enter, passively heating the building and reducing lighting and HVAC energy consumption.

Today, View Smart Windows are installed and designed into more than 92 million ft^2, including offices, hospitals, airports, educational facilities, government buildings, hotels, and residential buildings. Leading customers include Walmart, Google, Uber, FedEx, Stanford Healthcare, San Francisco International Airport and Dallas Fort Worth International Airport, as well as leading developers and real estate equity investors. In 2019, View Smart Windows were installed at the new Ontario Association of Architects headquarters as a part of a retrofit designed to help the building achieve zero-carbon operating use.

Technology History:

In 2007, View licensed DOE technology and began developing a large-scale, commercial EC window production facility. From 2010 to 2011, BTO invested in View Inc. to develop this technology, and it was commercialized in 2011. In response to success and growing demand for the product, View has grown its commercial manufacturing facility in Olive Branch, MS and raised over $1.5 billion in additional growth capital from investors in both private and public markets.

Applications:

- Used in offices, hospitals, airports, educational facilities and government buildings, hotels, and residential buildings

Capabilities:

- Controls radiant heat by blocking direct sunlight in summer and transmitting it in winter
- Reduces direct sunlight glare through windows
- Can be used as a demand response (DR) measure on peak summer days
- Complies with industry standard performance and reliability testing per ASTM E2141-06, ASTM E2190

Benefits:

- Enhances occupant wellness and productivity by reducing eyestrain, headaches, and drowsiness by over 50% relative to traditional blinds
- Reduces lighting and HVAC electricity consumption by 20% and peak cooling loads by 25%
- Reduces capital expenditures by allowing HVAC downsizing and eliminating blinds or shades
- Increases space utilization by maintaining thermal and visual comfort next to windows

Learn More:

- BTO Success Story
- DOE EC Windows
- DOE National Labs Make EC Windows a Reality

Contact

View, Inc.
195 S. Milpitas Blvd.
Milpitas, CA 95035
www.view.com

3.5 OptiQ™: An Advanced Commercial Window Technology

OptiQ™ double- and triple-pane insulating glass and insulating foam strips (LHS). Several building project installations using OptiQ™ (RHS)

Aluminum window framing systems are used in more than 80% of commercial buildings because of their inherently good structural properties and long service lifetime. However, these traditional window frames are poor insulators, which helps explain why windows are one of the least effective insulators in a building's envelope. Kawneer has developed a cost-effective, commercial-grade aluminum window frame with greater insulating capabilities than those typically found on today's market. OptiQ™ Ultra Thermal Windows (AATM4325) are 40% more effective at reducing energy losses than existing, commercially available, double-pane, low-emissivity (low-E) windows. They feature a polyamide thermal break, which allows them to achieve higher thermal performance than the traditional pour-and-debridge style thermal break.

OptiQ™ windows have thermally optimized frames with high performance glazing that are designed to accommodate double- or even triple-pane insulating glass. They are the first R-5 windows for the commercial buildings sector that have achieved an architectural structural rating. Additionally, they possess built-in thermal intelligence, making them one of the industry's smartest windows.

OptiQ™ windows have coefficient of heat transfer values (U-value) of 0.17 and 0.22 for fixed and operable windows, respectively—a performance level only previously attainable with nonmetal framing materials that reduced window structural integrity. OptiQ™'s improved thermal performance and excellent moisture resistance are obtained by using an advanced framing design with a polyimide thermal break and a highly insulating glazing system. Over the years, enhancements have been made to the structural performance of the OptiQ™ window platform, with hurricane testing and higher load design testing. These windows remain ahead of the building code requirements.

Technology History:

With American Recover and Reinvestment Act funding from the Department of Energy, Traco, a division of Kawneer, developed and commercialized OptiQ™ window frames in 2011. In 2013, Alcoa launched a horizontal and vertical sliding windows version of OptiQ™. As of 2021, tens of thousands of OptiQ thermal windows have been installed domestically.

Applications:

- Energy-saving replacement or alternative to conventional aluminum windows in commercial buildings for new and retrofit applications

Capabilities:

- Provides coefficient of heat transfer values (U-value) of 0.17 and 0.22 for fixed and operable windows
- Improves the U-factor of commercial-grade aluminum windows by >40% compared with market leading commercial window systems
- Enables R-5 architectural grade windows in commercial buildings
- Improves thermal comfort
- Improves condensation resistance (CR>72, CRF>78) and reduces likelihood of mold
- OptiQ™ currently exceeds building code requirements; enhanced structural design has undergone hurricane and higher wind load testing

Benefits:

- Comfort: increases both window insulating capability, which improves occupants' thermal comfort, and condensation resistance, which reduces formation of mold
- Cost savings: reduces heating and air-conditioning costs by inhibiting heat transfer through aluminum window frames
- Emissions reductions: reduces GHG emissions by decreasing heating and cooling energy consumption

Learn More:

- BTO Success Story

Contact

Kawneer North America
555 Guthridge Ct.
Technology Park/Atlanta
Norcross, GA 30092
www.kawneer.com

3.6 SageGlass®: Electrochromic Window Advanced Processing Technology

SageGlass' portfolio of products

Windows are often the most inefficient part of a building envelope. They are responsible for heat loss in cold months and solar heat gain in warm months. Sunlight entering a home can increase cooling loads by up to 20%. In some instances, glare from the sun can make it difficult to see a computer or other LCD screens, requiring the blinds to be pulled, negating the benefits of natural light. Sunlight can also fade furniture, carpets, and drapes, increasing building owners' maintenance costs.

With funding from BTO, SAGE Electrochromics Inc. developed SageGlass® product technology to create windows and skylights that switch from clear to dark with the push of a button. This EC glass modulates light transmission and solar heat gain by sending an electrical charge through the glass. The glass is made up of five separate layers of ceramic materials; when voltage is introduced, the glass lightens or darkens as needed. The electricity used to operate 1,500 square feet of SageGlass® window is less than a 60-watt light bulb. The glass can be configured to tint using either a predetermined algorithm that considers the sun's path and weather data, inputs from sensors, or a wall touch panel, integrated with building management systems or even a mobile app. The variable tint feature of the glass reduces glare, fading, and heat gain without losing the view. Without the drawbacks of traditional glass, this technology gives architects the freedom to design with daylighting, creating well-lit, comfortable buildings.

SageGlass® has a significant global presence in the EC glass space with more than 1,000 installs and over 1,000 issued patents, and there are currently three versions of the product commercially available. This includes the original SageGlass®, SageGlass LightZone®, which provides the ability to create up to three tint zones within a single pane of glass, and SageGlass Harmony®, which is the first EC glass to tint on a gradient. Within minutes, the EC glass completely changes, depending on the size and temperature of the pane.

Technology History:

SAGE Electrochromics Inc., a wholly owned subsidiary of Saint-Gobain as a part of the DOE Inventions and Innovations Program, was commercialized in 2007. It was selected by Commercial Architecture magazine to receive its 2016 Dynamic Glass Product of the Year in the windows and doors category. Additionally, it received the Top 101 Product recognition award from Building Design + Construction magazine, and recognition in the 2016 Green Design awards for two separate EC glass installation projects (the Museum of Science in Boston and the Rocky Mountain Institute Innovation Center in Colorado).

Applications:

- Can be used in a range of different building applications, such as higher education and healthcare facilities, airports, office buildings, and more, to reduce operating costs and increase cooling efficiency

Capabilities:

- Provides 60%–1% light transmission variability with the unique capabilities of in-pane zoning and gradient tinting
- Offers variable solar heat gain coefficients of 0.42–0.09
- With every pane of glass as a controllable unit, the glass can be configured and reconfigured to function based on the specific needs of the building and its occupants
- Can connect to smart building management systems, allowing building owners to control occupant comfort and energy efficiency

Benefits:

- Reduces annual cooling loads in commercial buildings by up to 20% and peak electricity demand in most of the United States by up to 26%
- Reduces HVAC requirements by up to 30%
- Offers a variety of tint colors to suit consumer preferences for differing applications
- Minimizes glare, reducing need for shades
- Reduces the fading of interiors and furnishing

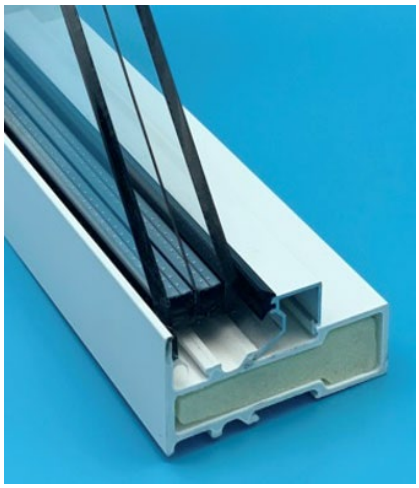
Learn More:

- BTO Article

Contact

SAGE Electrochromics, Inc.
2 Sage Way
Faribault, MN 55021
www.sageglass.com

3.7 Triple Glazing with Thin Non-Structural Center Glass



Cross-section of thin-glass triplepane window. Courtesy of Alpen HPP

Windows are a significant energy management weak point in a building's envelope. Energy spent mitigating the effects of unwanted heat transfer from windows is responsible for about 10% of building energy loads and about 4 quads of energy, annually nationwide. Energy-efficient, thin glass triple-pane windows have been identified as a potential method to improve window energy efficiency for the past few decades, but previous iterations of this glass technology were too costly to be used in new building construction or retrofits. However, recent technological advancements in thin glass technology have made the market viable for the implementation of thin glass triple-pane low-e coated windows.

Lawrence Berkeley National Laboratory (LBNL), with funding assistance from the Building Technologies Office and the California Energy Commission, has worked with industry partners including Alpen HPP, Renewal by Andersen, and Ply Gem to develop thin glass triple-pane window insulating glazing units that can be applied to new building construction or as a retrofit. Thin glass, triple-pane windows use three panes of glass and are coated with two low-e coatings, tightly sandwiched with spacers to create two sealed gas pockets that significantly enhance a window's insulative capacity. The gas pockets are filled with argon or krypton. Argon has traditionally been used for window insulation due to its nearly negligible cost, but krypton has been found to provide improved heat insulation at a greater cost.

The overall effectiveness of a window's resistance to heat conduction is rated with U-factor or its inverse, R-value, where a single pane of uncoated glass has an R-value of R1. The R-values of thin glass triple-pane low-e coated insulating glazing units have R-values up to R8, creating R5 or better windows, which are about twice as effective as high-end double-pane low-e windows, which have an R-value of R3 to R4.

Thin glass triple-pane windows have traditionally been more costly than typical windows, but as more triple-pane window products are introduced into the market, the price premium will decrease. The market effort is assisted through rebates with utilities, including Pacific Gas and Electric Company and Eversource, to encourage customer adoption of these higher-performance windows.

Technology History:

Thin glass, triple-glazed window technology was originally designed and patented by LBNL in 1989. However, due to a lack of viable sources for large sheets of very thin glass, the materials to produce these windows were prohibitively expensive for decades until the development of flatscreen TVs and phones allowed for an abundant, high-volume production source of thin glass. In 2017, LBNL restarted its efforts in the development and market deployment of thin glass, triple-glazed windows. Currently, products utilizing

Applications:

- Can be used to provide highly insulating, thin glass, triple-pane, low-emissivity-coated windows for installation in new construction or existing buildings

Capabilities:

- R-5 (U-0.2) with double hung windows
- No significant weight increases over double-pane
- Incremental cost comparable to equivalent wall or attic upgrades
- Uses existing window frame designs

Benefits:

- Improved insulation across windows compared to existing single or double-pane low-e glazed windows, significantly reducing heating and air-conditioning costs and increasing comfort
- Can potentially reduce energy usage in new construction by 7-16% depending on the location's climate
- Can potentially reduce buildings' carbon footprint due to using less energy because of mitigation of heat losses

Learn More:

- BTO Technology Page
- LBNL Technology Page

Contact

Lawrence Berkeley National Laboratory
1 Cyclotron Rd.
Berkeley, Ca 94720
https://windows.lbl.gov/

thin glass, triple-glazed windows are being commercialized as "drop-in" replacements for existing window frames designed for single or double-pane low-e windows. Other companies are further developing prototypes using this technology that may lead to the creation of additional products for the window market. LBNL is continuing its research into thin triple-pane windows by evaluating their energy savings across climate zones and developing next-generation thin triple-pane windows with fewer spacer leakage paths and thinner glass.	

4 Opaque Building Envelope and Thermal Energy Storage

The opaque envelope comprises all elements of the building envelope except for windows, including walls, roofs, and foundations. The opaque envelope affects 28% of building energy use, in particular that of HVAC systems. Air leakage through the building envelope is a key contributor to energy loss, and it is responsible for more than four percent of all primary energy used in the United States (DOE 2021). Implementation and adoption of novel, opaque envelope technologies could dramatically reduce energy use while simultaneously delivering additional benefits such as comfort, safety, and well-being for building owners and occupants.

4.1.1 Opaque Building Envelope

The use of high performance opaque envelope technologies, like advanced materials and systems, dynamic and controllable heat systems, and integrated TES, can lead to substantial reductions in building energy use. But to maximize energy savings, new technologies must be suitable for retrofitting existing buildings, particularly in the residential sector, where by 2050, three-quarters of the building stock will still be composed of "existing" buildings—those built before 2021 (ibid). For this reason, BTO focuses on R&D for technologies appropriate for both new building construction and retrofit applications.

With input from key stakeholders, the sub-program recently developed a research and development opportunities report titled *Opaque Envelopes: Pathway to Building Energy Efficiency and Demand Flexibility* that identifies technologies that have the greatest potential to transform opaque envelope performance in new and existing buildings. It lays out the critical technical and market barriers and challenges of the identified research opportunity areas and the R&D activities required to overcome them. The report will inform BTO's investments in developing the next generation of high performance, cost-competitive opaque envelope technologies, helping to achieve its overarching mission of decarbonizing the building sector.

The building envelope protects building occupants from undesirable outdoor environmental conditions. However, some envelope elements can be designed to take advantage of beneficial natural thermal energy (heat in the winter and coolness in the summer) from diurnal weather conditions, solar irradiance in the winter, and night sky cooling in the summer. Both strategies—leveraging desirable outdoor environmental conditions and mitigating the influence of undesirable conditions—can reduce energy use associated with HVAC equipment.

BTO's opaque envelope R&D efforts focus on dynamic and controllable heat systems, advanced tools, high performance materials and systems, envelope-integrated TES, and advanced building construction.

4.1.2 TES

To support the Energy, Emissions and Equity (E3) Initiative; GEB Initiative; and the Energy Storage Grand Challenge, BTO is focusing on TES research, development, demonstration, and

deployment to accelerate the commercialization and utilization of next-generation energy storage technologies for building applications. With thermal end uses (e.g., space conditioning, water heating, refrigeration) representing approximately 50% of building energy demand, which is projected to increase in the years ahead (BTO, "Thermal Energy Storage," n.d.), TES is seen as a key enabler for the large-scale deployment of renewable energy and a crucial component in the transition to a decarbonized building stock and energy system by 2050.

The sub-program seeks to identify a technology pathway to achieve 2030 targets of $0.05/kWh electric levelized cost of storage to enable widespread deployment of TES in buildings. This includes material-, component-, and system-level R&D. Advances in thermal energy storage can lead to increased energy savings, higher performing and more affordable heat pumps, flexibility for shedding and shifting building loads to reduce CO_2 emissions, and improved thermal comfort of occupants. Improving the temporal and spatial control of heat flows can further optimize the utilization of thermal storage capacity and reduce overall system costs.

Key R&D focus areas are dynamic and controllable heat transfer materials, high performance phase-change materials, thermal storage systems and integration, and thermochemical materials and reactor systems.

4.2 DuPont™ LiquidArmor™ Flashings: Advanced Energy-Saving Flashing and Sealant for Buildings

DuPont™ LiquidArmor™

Air leakage occurs when outside air enters and conditioned air leaves a building through cracks and joints in the building envelope, and accounts for significant energy losses. Air leakage also contributes to moisture problems that can affect occupants' health and the durability of materials in the building envelope. Reducing the amount of air that leaks in and out of residential and commercial buildings is one of the most cost-effective ways to lower energy consumption, cut heating and cooling costs, improve durability, increase comfort, and create a healthier indoor environment.

LiquidArmor™ CM and QS flashing products, developed by Dow Chemical (now DuPont de Nemours Inc. after a company merger and spin-off that took place in 2019), are an advanced sealing technology that has the potential to reduce energy losses related to air leakage by up to 50%. These are one-step liquid flashing products that can be brushed or sprayed on surfaces to seal gaps, cracks, and seams in the building envelope. Because they can be sprayed, LiquidArmor™ CM and QS can be installed up to three to four times faster than tape, another common flashing method. The product's fluid nature also allows them to "fill" and "bridge" gaps, reliably achieving a high-quality seal even in areas with complex shapes and on rough openings where windows and doors are installed. The elastomers adhere well to most surfaces, even as buildings settle or adjust to changes in temperature. LiquidArmor™ QS, launched in 2019, has the advantage of faster rain resistance and American Architectural Manufacturers Association 714 compliance over the original LiquidArmor™ CM flashing.

Both LiquidArmor™ CM and QS were subjected to rigorous testing at ORNL's Heat, Air, and Moisture (HAM) Penetration chamber during their development to demonstrate their capabilities and validate their performance under challenging conditions. The HAM chamber at ORNL can simulate indoor temperatures of 60°F to 90°F, outdoor temperatures of 0°F to 115°F, pressures from wind and wind gusts up to ±30 PSF, and subject walls to 10% to 90% relative humidity. Over the years, ONRL's HAM chamber has contributed to multiple versions of LiquidArmor™ tailored to different construction needs. This includes LiquidArmor™ QS, LiquidArmor™ LT, and LiquidArmor™ RS, beyond the original LiquidArmor™ CM. Each of the DuPont™ LiquidArmor™ product lines possess unique traits suitable for different working conditions and specific wall assembly designs. Dupont's decades of building science expertise, its portfolio of products, and its related technologies provide solutions that protect all six sides of any building envelope.

Technology History:

LiquidArmor™ CM and QS were developed by DuPont Performance Building Solutions and evaluated at ORNL before commercialization. BTO sponsored the ORNL-Dupont (Dow Building Solutions) collaboration through the U.S.-China Clean Energy Research Center for Building Energy Efficiency, which supports the development of advanced technologies to reduce energy consumption and CO_2 emissions in the United States and China. In 2014,

Applications:

- Sealant and window flashing for commercial and residential wall systems

Capabilities:

- Only one-step, sprayable liquid flashing on the market
- 3 to 4 times faster to install than flashing tapes
- Adheres to different substrates (i.e., concrete, steel, wood, aluminum, foam insulation, gypsum board)
- Easily conforms to complex geometries to form a tight, durable, seamless barrier along the rough openings of windows and doors
- Penetrates and seals hard to reach gaps up to a ¼ inch wide without a supporting material

Benefits:

- Reduced air leakage through the building envelope
- Decreased energy use from heating and AC systems
- Reduced labor time and expenses for installation
- 100% of the electricity used to make LiquidArmor™ comes from renewable energy sources

Learn More:

- BTO News Article
- BTO Success Story
- BTO Project Page
- Product Portfolio

Contact

Dupont de Nemours, Inc.
947 Centre Road,
Wilmington, DE 19805
www.dupont.com

LiquidArmor™ CM was commercialized in the United States. It was recognized as an R&D 100 Award Finalist in 2015 and won the 2016 Gold Edison Award for Building Construction and Lighting Innovations.	

4.3 IC Solar Envelope: Energy-Efficient Facades for Green Buildings

IC Solar Array installed in clerestory of proposed FIT expansion (render). NY, NY

As buildings consume roughly one-third of global primary energy, more effective strategies are required to convert on-site solar energy. The IC Solar Envelope (IC Solar) addresses this need by encasing tracking concentrator photovoltaics (CPV) within a deep-mullion fenestration unit, resulting in three to four times the site energy benefits of currently available photovoltaic (PV) technologies. IC Solar provides views and diffuses daylight for occupants while generating power as well as the associated benefits of solar gain reduction. The array is designed to integrate architecturally into the envelope of a building: its facades, clerestories, roofs, and atria. IC Solar's modular design complements a range of existing building structures. As an architectural daylighting system, IC Solar significantly reduces mechanical cooling system costs while simultaneously capitalizing on high-efficiency concentrating photovoltaic cells with active heat capture and transfer, resulting in a highly integrated and powerful system for both energy savings and energy production.

The multiple benefits of IC Solar are accomplished by miniaturizing and distributing components of CPV technology within a weather-sealed building envelope. To maintain optical alignment throughout the day, IC Solar actively tracks the sun with simplified mechanical linkages. Diffused sunlight filters through the array's transparent components, providing daylighting deep into a floorplate, but reducing glare and heat by intercepting and optically concentrating direct solar energy onto small ($1cm^2$) multijunction PV cells, which are more efficient than (and tolerate temperature increases better than) silicon-based PV. A coolant loop joining heat exchanger bonded to each individual PV cell captures and collects any unconverted solar gains into hydronic storage. This heat can be vented, be applied to heating demands or process hot water, or used to drive sorption-based systems such as dehumidification and solar cooling.

Technology History:

IC Solar was developed by the Center for Architecture Science and Ecology at Rensselaer Polytechnic Institute, with assistance from EERE, the New York State Energy Research and Development Authority, and the Empire State Development's Division of Science, Technology, and Innovation. IC Solar was commercialized beginning in 2011 and is licensed by HeliOptix LLC. Development continues through ongoing collaboration with the University of Rochester's Institute of Optics (which demonstrated at the DOE Advanced Research Projects Agency – Energy's Energy Innovation Summit in 2019) and the Yale University Center for Ecosystems in Architecture, through which the first public installation of IC Solar was included in the United Nation's Ecological Living Module demonstration (New York City, 2018).

Applications:

- Integrates into building envelope (facade, clerestories, roof, and atria) to enhance daylighting, reduce solar gains, generate electricity, and control heat transfer

Capabilities:

- Provides diffuse daylighting, reduces glare
- Generates electricity (185 Wp/m^2 at concentrating standard operating conditions) and hot water (235 Wp/m^2)
- Reduces solar transmittance through glazing by 70–90%

Benefits:

- Reduces a building's cooling and lighting requirements and generates power at near-peak time to reduce electricity costs
- Modular design easily integrates with a variety of existing or new designs
- Reduces emissions by using renewable solar energy to meet building electrical and thermal loads

Learn More:

- Final Report
- Recent Material
- FIT Building

Contact

HeliOptix LLC
233 Broadway 11th Floor
New York, NY 10279
www.helioptix.com

4.4 Air Barriers 3M 3015

Photo courtesy of 3M

Building heating, cooling and ventilation consumes 9.5 quads of energy per year or 59% of the energy used in buildings nationally (EIA, 2015 RECS (Table CE3.1) and 2012 CBECS (Table E1) Survey Data 2015 (RECS); 2012 (CBECS)).

Energy conservation research has included the evaluation of building construction and materials to increase potential savings. Initially, improvements to building envelopes focused on augmenting thermal resistance by using better performing materials. To further reduce HVAC loads, limiting air leakage was investigated; air leaks can cause deterioration in envelope materials, and air drafts can compromise comfort. Air barrier materials are a proven technology that can stop air from leaking through the building enclosure and reduce its corresponding energy penalties. However, proper installation of air barriers remains a major obstacle for achieving air barrier systems that meet the 2021 International Energy Conservation Code requirements.

With funding from BTO, the 3M Company, in collaboration with ORNL, evaluated the performance of the 3M 3015 self-adhered membrane.

Technology History:

Developed by the 3M Company, 3M 3015 became available in the market in 2016 and was identified as potentially contributing to meet LEED EA Optimized Energy Performance points. 3M is phasing out the current 3015 Air Barriers over time in favor of their new, robust nonpermeable product 3015NP, which was released in 2021. This new 3015NP product has a multilayer film backing and uses an acrylic adhesive with a polycoated Kraft liner.

Applications:

- Can be used to improve air tightness of new and existing residential and commercial buildings

Capabilities:

- Improves building performance, thereby decreasing HVAC loads and equipment size
- Improves occupant comfort by minimizing air drafts

Benefits:

- Saves energy by reducing HVAC equipment loads
- Improves building envelope construction practices, preventing deterioration of materials and costly repairs and/or replacement

Learn More:

- BTO Project Page
- Technology Verification Page
- 3015 Technical Data Sheet

Contact

3M Center
Building 230-2F-255A, MS-6070
St. Paul, MN, 55144-1000
www.3m.com/construction

4.5 Precast Concrete Molds Using 3D Printing Technology

Domino Sugar Refinery Development and 3D-Printed Mold and Precast Window

Precast concrete parts usually use wooden forms, which can require labor-intensive assembly steps. Although metal forms are typically used for higher volume precast concrete components, wooden forms are still used for architectural pieces that are usually cast in smaller batches or one offs. In 2018, Gate Precast won a contract to produce over 1,500 precast punched window components for the 42-story One South First building in the Domino Sugar Refinery development project in Brooklyn, New York. This contract would have been exceptionally challenging, time intensive, and labor-intensive using traditional wood forms and would not have met the accelerated timeline set by the builder.

ORNL and industry partners, with support from BTO and the Advanced Manufacturing Office, developed a 3D printing process for molds to be used by the precast concrete industry. The 3D-printed molds are made of a carbon fiber reinforced polymer. Through the manufacture of the precast facade for the One South First building, it was demonstrated that the 3D-printed molds are 10 times more durable than wood molds. Each mold starts off as a CAD model and takes approximately 8–11 hours to print; traditional wood and fiberglass molds can take three to four days to complete by comparison. The 3D print is then finished on a computer numerical control router machine. The overall fit and finish of the 3D-printed molds is superior to the traditional wood counterparts. ORNL and its research partners identified solutions for thermal warping and provided tips on how to maintain and repair the 3D-printed molds (e.g., dings, holes, and laminar bead separations).

The precast concrete parts are poured in the 3D-printed molds and cured for 12 hours, demolded, and surface finished. Windows are installed in the precast parts before transportation to the construction site. The ability to precast these components enabled time savings by shifting assembly away from the building site. 3D-printed molds give architects significantly more flexibility to incorporate innovative shapes into their designs, which is an opportunity to integrate more energy-efficient design strategies into their buildings. In the One South First building, the 3D-printed molds were designed to provide overhangs that varied with each cardinal direction and reduce solar radiation indoors.

Technology History:

The idea for 3D-printed molds for construction was conceptualized in 2018 and went from conception to commercialization in about a year and a half. ORNL partnered with Gate Precast to build the first molds for precast concrete that were used to create the concrete facade for the One South First building. Molds were printed using a Cincinnati Big Area Additive Manufacturing machine and the material used for printing was carbon fiber reinforced acrylonitrile butadiene styrene, a common thermoplastic.

Applications:

- Precast concrete components for multifamily and commercial buildings

Capabilities:

- 3D-printed molds give architects/builders the ability to integrate more energy-efficient design strategies into their buildings
- 3D-printed molds are durable and can be used to pour at least 200 parts compared to the 20 pours from typical wood molds

Benefits:

- Shorter manufacturing time of complex molds compared to hand-assembled wood molds
- Ability and additional flexibility for integrating more energy-efficient designs

Learn More:

- BTO Project Page
- Gate Precast One South First Building

Contact

Oak Ridge National Laboratory
P.O. Box 2008
Oak Ridge, TN 37831
www.ornl.gov

5 Lighting

Traditional lighting technologies have little leeway for improvements in efficiency, but SSL, particularly LED-based technology, still has significant room for growth in achieving its full potential. In the United States today, LED lighting is already saving an estimated 140 billion kWh in annual energy savings, equating to 98 million metric tonnes of avoided CO_2 emissions per year and $14.7 billion in avoided energy costs for U.S. businesses and other consumers (DOE 2020).

According to DOE projections, if DOE targets for efficiency, controls, and connectivity are met, then these advanced lighting systems are expected to save 22.8 million GWh of electricity. The total cumulative energy savings would be equivalent to $890 billion in avoided energy costs and 5.9 billion metric tons of avoided CO_2 emissions (DOE Office of Energy Efficiency and Renewable Energy 2019).

LED technology provides new capabilities, including the ability to deliver any combination of colors. The spectrum can be dynamically engineered to optimize health, safety, and learning—as well as the eye appeal of produce—while saving carbon emissions, energy, and associated costs compared to legacy technology.

BTO's Lighting R&D fosters U.S. scientific capabilities, leverages private funds, provides internationally trusted information, and drives innovation to create efficient and flexible lighting products that support health, productivity, and well-being.

- Platform technology R&D lowers barriers to adoption, decreases performance tradeoffs, and improves lighting application efficiency through advances in materials, components, device structures, product integration, and manufacturing technology.
- Integration and validation studies evaluate advanced lighting solutions and design strategies in real settings.
- Lighting science and analysis research informs productivity benefits and lighting application efficiency and improves our understanding of how best to apply new capabilities enabled by LED lighting.

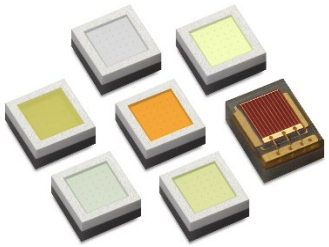
For nearly two decades, BTO's Lighting R&D has played a key role in driving SSL technology advances. The 335 competitively selected R&D projects funded to date have resulted in 431 patents (applied for or awarded) and the direct development of 346 commercially available, state-of-the-art products by U.S. companies. However, the actual impact of the BTO Lighting R&D sub-program is far greater than indicated by that figure, which only includes products directly developed or enabled by DOE R&D funding and does not include the millions of derivative, influenced, or next-generation products that are based on projects that received direct DOE support.

In many instances, DOE funding led to the development of widely used product platforms or to materials that have gained widespread adoption and are now found in tens of thousands of

specific products with millions of individual units sold. Likewise, DOE-funded improvements to production tools have increased product consistency, quality, and yield and have led to cost reductions in LED lighting components and products worldwide.

Between 2015 and 2020 alone, 101 new products directly resulted from Lighting R&D program funding. The following summaries highlight cutting-edge products that advanced the state-of-the-art—from performance improvements in cyan and green LEDs used in tunable lighting products, to organic LED (OLED) panels in different shapes, color temperatures, and finishes, to tunable classroom lighting products and controls, to flexible lightguide technology. For a full list of commercialized products between 2015–2021, see Appendix A.

5.1 Lumileds LUXEON® LEDs



Lumileds' LUXEON Rubix family of color LEDs

Although LEDs have progressed significantly in the last decade, the efficiency of LED lighting still has considerable room to improve and we are only halfway to the efficiency threshold needed to enable low-loss, color-mixed LEDs that avoid losses from phosphor-converted products that predominate today's market. Researchers continue to drive advances toward the practical limit of 255 lm/W for phosphor-converted LED architectures. With further breakthroughs, particularly for green and amber LEDs, there is potential to reach the ultimate theoretical limit of 325 lm/W for direct emitting architectures that combine color LEDs to make white light. Scientists and engineers at Lumileds have been instrumental in driving LED technology and performance advancements. These innovators continue to work at the cutting edge of LED technology to improve efficiency and all aspects of lighting performance, including color, intensity, and optical control.

With support from BTO, Lumileds R&D projects have boosted many aspects of LED performance and lowered their cost. These improvements map into multiple Lumileds product lines, including the LUXEON family of LEDs, and have been incorporated into millions of LED lighting products on the market.

A recent BTO-funded R&D project at Lumileds focused on understanding the physical mechanisms of current droop, which limits LED performance at higher current density and therefore higher intensity. Mitigating droop enables new higher brightness lighting applications and improves the economics of LED lighting since more light can be generated per area of LED. Lumileds R&D on droop has led to dramatic performance advancements for Lumileds' cyan and green LEDs. Green and cyan LEDs are more susceptible to the underlying physical mechanisms of droop than blue LEDs, and the advanced understanding gained from this research project led to improvements in green and cyan LED device design, resulting in improved efficiency. These LEDs are used in color-tunable lighting products, architectural lighting, or lighting that is tailored for human physiological responses in classrooms and healthcare settings, for example. Advancements in these colored LEDs are also critical for transitioning to direct emitter lighting architectures that use no phosphor, an approach considered key to achieving the ultimate efficiency potential for LED lighting.

Technology History:

More than 200 Lumileds product stock keeping units have been developed as a direct result of DOE lighting R&D funding. Lumileds is an LED market and technology leader based in San Jose, CA. It supplies billions of LEDs to millions of energy-saving lighting products.

Applications:

- Can be used across the full spectrum of lighting applications, including color-tunable lighting products, architectural lighting, or lighting that is tailored for human physiological responses

Capabilities:

- Highly energy-efficient
- Directional, dimmable, and vibration-resistant
- Instant-on
- Color-tunable (in some cases)
- High performing

Benefits:

- Reduces energy costs
- Cuts down on carbon emissions
- Reduces maintenance costs
- Reduces wasted light
- Provides excellent lighting quality
- Provides non-energy benefits such as improving health and productivity

Learn More:

- BTO Research Highlights
- BTO Research Highlights
- BTO Research Highlights
- BTO Research Highlights
- BTO Research Highlights
- BTO Project Webpage
- BTO Peer Review Presentation
- BTO R&D Impacts Success Story

Contact:

Lumileds
370 West Trimble Road San Jose, CA 95131 www.lumileds.com

5.2 Finelite FineTune® TCS

Finelite's FineTune® Tailored Control System

Lighting energy costs are a large operational expense for schools and universities, but previous energy conservation strategies for classroom lighting have typically reduced lighting quality and bypassed opportunities for increasing student engagement and teacher satisfaction.

With funding from BTO, Finelite partnered with RTI International to develop and validate an LED-based next-generation integrated classroom lighting system. Finelite built a model classroom with luminaires and controls, where more than 80 teachers and school administrators participated in focus groups over a 12-month period. The purpose was to provide input on the use of advanced lighting technologies in the classroom and gain feedback on the design of the user interface for the lighting control system. At the same time, RTI conducted research and accelerated stress testing in extreme conditions to verify the system and device wear-outs.

The FineTune® TCS plugs together control stations, switches, control packs, sensors, and LED luminaires to create a lighting system that is scalable, affordable, and easy to install. This lighting system offers continuous tunable white light ranging in color between warm white (2700K) and cool white (6500K), delivered at a luminous efficacy >125 lm/W at all color temperatures. Integrated sensors can harvest daylight in the classroom and selectively dim luminaires to maintain a constant lighting level, further reducing energy consumption. The product offers a full suite of luminaires and controls that enable adjustment of the color from the luminaires, tuned between warm white and cool white settings to elicit physiological and behavioral responses from students.

The system enhances the learning experience by providing a state-of-the-art lighting environment that easily adjusts the lighting conditions—both color and illuminance levels—to the task at hand (e.g., general, screens, video, focus, energize, calm). The system is equipped with easy-to-understand controls and research-driven factory preloaded scenes that are customizable for the classroom users.

Technology History:

The Finelite/RTI International project to develop and test "Luminaires for Advanced Lighting in Education" began in 2015. The project completed in 2017 and FineTune TCS was commercially introduced in 2019.

Applications:

- Suitable for learning facilities, healthcare applications, commercial spaces, houses of worship, institutional buildings, and retail buildings

Capabilities:

- Scaled system architecture flexible enough to fit any project size
- Out-of-the-box ready for static white or tunable white luminaires
- Built-in code compliance, commission-free, and plug-and-play wiring for 0–10V and DMX
- User-friendly control with factory preset scenes

Benefits:

- State-of-the-art, layered lighting control
- Designed with user input and validated by research
- Highly customizable and user-friendly system

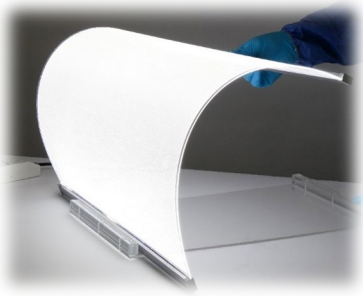
Learn More:

- BTO Research Highlights
- BTO Field Evaluation

Contact:

Finelite, Inc.
30500 Whipple Road
Union City, CA 94587
www.finelite.com

5.3 Lucent Optics Ultra-Thin Flexible LED Lighting Panels



CoreGLO™ by Lucent Optics

Beyond light bulbs, SSL technology enables new flexible form factors with the potential to deliver light more efficiently, with reduced materials and costs. Lucent Optics has developed a scalable technology platform for making wide-area LED lighting panels with thin and flexible forms, optical waveguides, and LED illuminated waveguide edges. The waveguide is essentially a thin sheet of clear plastic used to distribute light from the LEDs over the entire area of the panel. The waveguide carries a very fine surface pattern for progressively extracting that light and emitting a soft, uniform glow from the panel's surface. For waveguide patterning, Lucent Optics employs a proprietary additive manufacturing process called microprinting. Microprinting converts raw plastic sheets into high performance surface-emitting optical waveguides in a matter of minutes, without having to process the plastics thermally or chemically.

Using this technology platform, Lucent Optics developed CoreGLO™ technology for general lighting applications. These high performance LED lighting panels combine ultrathin and flexible form factors with more than 100 lm/W luminous efficacy. The platform enables new luminaire design opportunities previously unattainable with conventional form factors and lower costs of manufacturing.

Initially, Lucent Optics commercialized key components of CoreGLO panels, including microprinted optical waveguides ranging in sizes from 8″ × 12″ to 24″ × 24″ as well as low-profile LED strip engines compatible with these waveguides. Continued technology development, aided with support from the DOE SBIR Program, led to waveguide offerings in larger sizes and the launch of the first integrated product: the CoreGLO LED lighting panel. This panel is available in several standard configurations and as a fully customizable product. It can be configured for one-sided or two-sided emission (e.g., for direct/indirect lighting) and transparent or translucent appearance at wall-plug efficacies of up to 121 lm/W. Available options also include different color temperatures and color rendering, as well as a selection of decorative emission patterns.

Customers include manufacturers of electronic displays, illuminated signs, and lighting products. The optical waveguides and backlighting structures of Lucent Optics' patented designs can also be found in a variety of mass-produced consumer products ranging from handheld devices (e.g., smartphones and tablets) to computer monitors and flat-panel televisions.

Technology History:

Lucent Optics began working on flexible waveguide illumination technology over a decade ago, initially focusing on backlit displays and specialty lighting applications. With the help of DOE SBIR funding, the technology was further developed and adapted to general lighting by creating a cost- and material-efficient LED/waveguiding panel, improving the efficiency of light coupling and extraction, and employing a scalable additive manufacturing process for making high performance optical waveguides from plain plastic sheets.

Applications:

- Architectural lighting, general lighting, and backlighting for electronic displays and illuminated signs

Capabilities:

- Thin, wide-area LED source enabling curved and flexible sheet-form lighting solutions
- New luminaire design opportunities previously unattainable with conventional SSL form factors
- Combining >80% luminaire-level optical efficiency with uniform all-surface emission
- Highly customizable size, thickness, transparency, and spatial and angular distribution of the emission

Benefits:

- Lower costs of manufacturing, shipping, and installation due to reduced material intensity, low weight, and compact form
- Unique, aesthetically pleasing appearance with virtually unlimited forms and design options
- Glare control without adding volume and raw materials

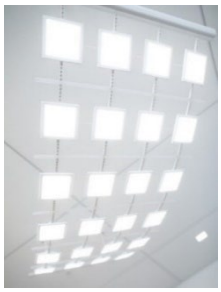
Learn More:

- SBIR Success Story
- 2020 Lighting R&D Workshop Poster

Contact:

Lucent Optics
1832 Tribute Road
Sacramento, CA 95815
www.lucentoptics.com

5.4 OLEDWorks Brite 3 OLED Lighting Panels



LumiCurve Wave Brite 3 OLED technology

Historically, there has been a perceived tradeoff between lighting quality, such as diffuse sources, and efficiency, which often benefits from high illuminance sources that can appear glaring. A key priority for DOE Lighting R&D is moving beyond these tradeoffs, and diffuse direct emitters such as OLEDs offer a path forward. These technologies provide options for luminaire design since the lighting can be placed close to the object or occupant being lit. OLED luminaires illuminate space with flexible, glare-free, and uniform light while providing energy savings.

OLEDWorks is the only manufacturer of OLED lighting panels in the United States. OLED light sources are available in several shapes and sizes, with warm (3,000K) or neutral (4,000K) color temperature, all while providing high color quality (90+ Color Rendering Index).

With funding from BTO and the SBIR Program, OLEDWorks has been able to continually improve the efficacy, brightness, lifetime, and reliability of OLED lighting panels while lowering their cost.

OLEDWorks' Brite 3 family of OLED lighting panels includes 12 different products with different shapes, color temperatures, and finishes. With an efficacy up to 85 lumens per watt (lm/W) and lifetimes exceeding 100,000 hours, Brite 3 OLED lighting panels are finding their way into an increasing number of commercial and residential luminaire applications. The Brite 3 OLED products were commercialized in 2018, succeeding the earlier generation Brite 2 OLED products. These high performing white OLED lighting panels are based on an integrated light extraction substrate with a multi-stack white OLED architecture. This technology was partially developed with funding provided by several DOE BTO and SBIR programs starting in 2013 and continuing through today.

The Brite 3 family also includes the LumiCurve Wave, a flexible OLED lighting panel based on ultrathin glass. Developed in a joint collaboration with Corning and further supported with DOE SBIR funding, this panel boasts a slim profile with less than 0.5mm thickness.

Technology History:

OLEDWorks was formed in 2010 by a group of technologists from the former Eastman Kodak OLED business unit in Rochester, New York. In 2015, the former Philips OLED lighting business in Aachen, Germany became the high-volume manufacturing arm of OLEDWorks. The Brite 1 product family was introduced in 2014 by Philips with an efficacy of 45 lm/W. After the acquisition by OLEDWorks,

Applications:

- Office and commercial space lighting, automotive lighting, embedded lighting for transportation, recreation, medical use, machine vision, and other custom/specialty lighting applications

Capabilities:

- Easy integration into single or multi-panel luminaires with new and beautiful form factors
- Enables applications requiring thin, lightweight, and highly uniform light sources
- Flexibility/curvature
- Segmentation to allow digital lighting effects with individually controllable lit segments

Benefits:

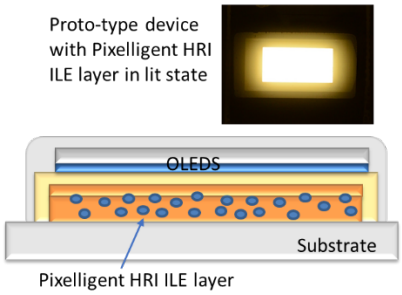
- Energy-efficient
- Excellent lifetime and reliability
- Glare-free and dimmable
- Provides non-energy benefits to support health and comfort

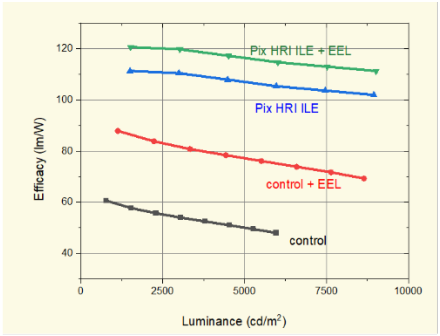
Learn More:

- BTO R&D Impacts Success Story
- BTO Research Highlights
- BTO Research Highlights
- BTO Research Highlights
- BTO Project Webpage
- BTO Project Webpage

the Brite 2 family was introduced in 2016 with an efficacy of 63 lm/W, to be succeeded in 2018 by the current Brite 3 family of OLED lighting panels. Today, OLEDWorks remains the only manufacturer of OLED lighting panels in the United States.	**Contact:** OLEDWorks 1645 Lyell Avenue, Suite 140 Rochester, NY 14606 www.oledworks.com

5.5 Pixelligent Light Extraction Materials





Diffuse light sources such as OLEDs offer a flexible, glare-free option for luminaire design. However, current OLED lighting is limited by low light extraction efficiency, even though they have very high internal light-production efficiency. Pixelligent Technologies' research, funded through the DOE SBIR Program, focuses on developing advanced, cost-effective materials for OLED lighting. Their work has advanced the materials science used to create internal light extraction (ILE) layers for use in OLED panels through the use of high-refractive-index (HRI) layers that are embedded with light scattering particles.

In 2017, the team developed a novel ILE design to improve the light extraction efficiency of OLED lighting devices to 70% without negatively impacting the device voltage, efficiency, or angular color dependence. The innovative structure is positioned between the OLED device stack and the glass or polymer substrate, enhancing light outcoupling by reducing waveguiding losses in the OLED stack. These losses occur due to reflections resulting from an index of refraction mismatch at the device/substrate interface. Pixelligent's ILE combines scattering particles in an HRI matrix. The HRI matrix has an index of refraction between that of the device stack and the substrate, resulting in fewer interfacial reflections and waveguiding losses. The larger (hundreds of microns) titanium dioxide scattering particles embedded in this matrix serve to scatter light out of the device. This HRI-ILE technology is enabled by Pixelligent's proprietary, HRI, highly transparent zirconium oxide ($ZrO_{2)}$ nanocrystals. Extensive research has been conducted to optimize the index of refraction of the ILE materials, determine the appropriate scattering size and loading densities, and formulate the materials for proper particle distribution and processibility.

In subsequent projects, the team utilized the extremely small size of the HRI nanoparticles to create gradient index films with a simple coating process. The team has continued to optimize the process for gradient film manufacturing and the scattering layer configuration and processing.

Pixelligent teams with OLEDWorks to demonstrate their cost-effective, HRI nanocomposite formulation in a well-characterized OLED device manufactured by OLEDWorks. In 2021, the manufacturability testing was demonstrated with OLED devices built on large-area integrated substrates. Recently, Pixelligent's HRI-ILE integrated OLEDs demonstrated an efficacy as high as 117 lm/W at 3,000 cd/m^2 with a Duv <0.008 and color rendering index (CRI) of ~84 in prototype devices. In comparison, the efficacy of the state-of-the-art OLEDWorks Brite 3 panel (currently available on the market) is 85 lm/W. With the OLED lighting market moving toward niche applications, such as bendable light panels, Pixelligent's ILE has also successfully been tested in flexible prototype devices.

Applications:

- Pixelligent supplies novel materials found in a variety of OLED panels

Capabilities:

- Novel light extraction materials improve the efficiency and lifetime of OLED devices
- Pixelligent materials and methods are compatible with multiple OLED manufacturing approaches

Benefits:

- Energy-efficient, thin, lightweight, and glare-free OLED lighting solutions enable lighting to be placed close to the object or occupant being lit

Learn More:

- BTO Project Webpage
- BTO Project Webpage

Contact

Pixelligent Technologies LLC
6411 Beckley St #6538 Baltimore, MD 21224
www.pixelligent.com

Technology History:

Pixelligent is a leading high-index advanced materials manufacturer, leveraging nanomaterials to develop high-quality dispersion technology for next-generation products in solid-state lighting, AR/MR, sensors, and optical coatings applications. Pixelligent's PixClear® zirconia and titania dispersions and PixNIL™ and PixJET™ formulations deliver high refractive index, transparency, and stability in novel materials supplied to OLED manufacturers. In 2018, Pixelligent commercialized their ILE formulations, which are fully compatible with multiple OLED device manufacturing processes and operating conditions, helping to expedite the commercialization of OLED lighting. HRI-ILE OLEDs are cost-effective due to the use of highly scalable materials and the low-cost manufacturability of Pixelligent materials.

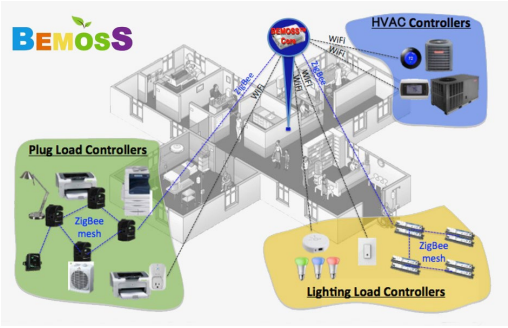
6 Building Controls

Supervisory building controls enable a buildings operational infrastructure to make predetermined decisions that optimize specific parameters related to the timing and amount of energy use and make real-time changes to meet occupant needs and improve energy productivity while also providing grid benefits. By leading innovative research to drive advancements in control theory and applications, BTO can help building owners, operators, and end users harness the energy storage and demand flexibility potential of buildings to increase and enhance the penetration of energy efficiency and renewable generation at scale. In turn, this can open up new market and financial opportunities to further enable buildings' contribution to reducing energy use and GHG emissions.

A 2017 report highlighted that up to 30% of building energy consumption can be eliminated through the use of more accurate sensing, more effective use of existing controls, and the broader deployment of advanced controls (PNNL 2017). In addition, more sophisticated analytics and control strategies—including machine learning and model predictive control—can help achieve another 10% reduction in total building energy consumption. Overall, this combined energy savings potential could deliver approximately 1.4 quads of energy savings by 2030 and 3.8 quads in 2050 across applicable end uses (BTO n.d.). Through the minimization of preventable energy losses and the optimization of environmental, equipment, and occupant parameters, BTO's building controls research aims to realize this energy savings potential in support of its overall energy savings goals.

BTO invests in controls R&D to accelerate the transition from simple, reactive controls to optimized, whole-building controls designed to meet energy efficiency, demand flexibility, and occupant comfort objectives. The next generation of supervisory building controls will incorporate predictive, adaptive, and robust control with multi-objective optimization techniques to provide explainable (intelligible) solutions to building owner, occupant, and operator needs. It will be characterized by automated and continuous commissioning to extend equipment life, reduce the possibility of failures, and save energy. It will include market-based coordination techniques that securely negotiate with the grid to respond within a required timeframe and provide the requested service to the grid within acceptable occupant comfort and productivity constraints. Supervisory controls can also coordinate operations of various building technologies with on-site electricity generation and storage for enhanced energy efficiency and cost savings.

6.1 Building Energy Management Source (BEMOSS) SDK



Bemoss Architecture for Small to Medium Sized Buildings

In the United States, commercial building electricity consumption was over 4 quads at a cost of over $120 billion ((EIA 2012)). Commercial buildings have high energy needs and can put great strain on the nation's power grids during peak periods. A large portion of energy consumed in buildings is wasted, which building automation systems could help avoid, but these systems are expensive for small- to medium-sized building owners and managers to purchase.

With support from the BTO, Virginia Tech University, Arlington County, Virginia, and Danfoss Corporation developed BEMOSS, a building energy management software designed to monitor and control equipment in small-to-medium-sized commercial buildings. BEMOSS optimizes building electricity use to reduce energy consumption and implement DR signals from the grid. The system is designed to operate with existing building controllers (HVAC, lighting, and plug loads), which makes building energy management systems more affordable to install. The development of BEMOSS began in 2014 before it was field-validated within several commercial buildings over various sizes from 2016 to 2017, where it yielded higher energy efficiencies of approximately 10–15% with 30% efficiency improvements for lighting. BEMOSS delivers energy savings and peak demand reductions in small-and medium-sized commercial buildings up to 50,000 ft^2.

In 2016, BEM Controls LLC commercialized the BEMOSS software platform in a product called WiseBldg (www.bemcontrols.com). BEM Controls' platform provides an open-architecture software platform for monitoring and controlling major energy systems (e.g., HVAC, lighting, and plug loads), as well as security cameras, solar PV systems, energy storage units and other Internet of Things (IoT) sensors in commercial buildings. The platform has embedded algorithms that can learn from archived building operational data and occupant preferences to allow commercial buildings to save energy (kWh), reduce peak demand (kW), and participate in DR markets.

Technology History:

BEMOSS development began in 2013 at Virginia Tech and received DOE funding to develop the concept further in 2015. Virginia Tech's research team formed a spin-off company, BEM Controls LLC, to bring the technology to market, which commercialized the BEMOSS software platform in a product called WiseBldg (www.bemcontrols.com) in 2016.

Applications:

- Cost-effective BEM application development with OpenStudio SDK for small- to medium-sized commercial buildings

Capabilities:

- Open-source cross-platform collection of modules for BEM application development
- Supports communication technologies: Ethernet, Serial, and Wi-Fi; and protocols: BACnet, Modbus, Web, and OpenADR
- Compatible with existing HVAC, lighting and plug load controllers for plug-and-play interoperability

Benefits:

- Enables rapid, low-cost development of new BEM applications and analyses by integrating with exiting systems
- Enables on-site, remote, and mobile access to a building's BEM system
- Provides implementation of DR monitoring for solar PV and energy storage systems

Learn More:

- BTO Project Page
- 2017 Peer Review

Contact

Virginia Tech Research Center - Arlington
900 N. Glebe Road
Arlington, VA 22203
www.bemoss.org

6.2 Molex Wireless Sensors – Energy-Harvesting, Self-Calibrating x Sensors for Building Equipment

Molex's Peel Stick Energy Harvesting Wireless Sensor

Traditional HVAC units in buildings often tend to be under-, or poorly, controlled, leading to wasted energy. While HVAC systems, and other building systems such as lighting, would benefit from additional monitoring that could lead to better performance, many conventional sensors, both wired and remote, are cost prohibitive. Additionally, there has been a technology gap in wireless sensors with reliable self-powering mechanisms and a lack of manufacturing and signal processing techniques. Low-cost energy harvesting-based wireless sensors could enable building system and equipment monitoring necessary for whole-building control and improved building energy efficiency.

In partnership with Molex and Palo Alto Research Center and with funding from BTO, ORNL developed and demonstrated low-cost wireless sensors manufactured using roll-to-roll (R2R) manufacturing techniques. The R2R manufacturing enables electronics components such as circuits, sensors, antennae, PV cells, and batteries to be integrated on flexible, printed plastic-based thin film materials. ORNL's wireless sensor platform is designed to monitor multiple environmental factors within a building (e.g., temperature, humidity, light levels).

ORNL and its partners' system-level integrated energy-harvesting wireless sensor technology have significant range, which reduces networking infrastructure. The sensor and supporting components can be used in new building installations or retrofitted in existing buildings. Through BTO's manufacturing partner Molex, commercially produced self-powered wireless sensors have been successfully demonstrated. Both thin film sensors printed using inkjet printing of silver and multifunctional devices using additive R2R techniques have also been demonstrated.

Technology History:

Development of ORNL's wireless sensor platform began in September 2013 and transitioned to a cooperative R&D agreement with the electronics manufacturer, Molex, in 2015. Additionally, ORNL has partnered with OEMs in the buildings sector to identify suitable sensor applications. Through separate funding from the Buildings Energy Efficiency Frontiers & Innovation Technologies (BENEFIT) funding opportunity announcement awarded in 2016, the ORNL-led team has also investigated extending the lifetime of the on-board power source by improving the efficiency of the energy harvester. The technology was commercialized in 2019 by Molex and a new flexible current sensor is in development.

Applications:

- Monitor building parameters, enable fault detection and diagnosis of building equipment, and improve energy efficiency through whole-building control

Capabilities:

- Provides information for optimal control of energy-consuming systems
- Versatile, customizable, and modular design with peel-and-stick installation
- Reduces building monitoring system installation and maintenance cost
- Provides optimized network communication to reduce networking infrastructure and improve energy efficiency

Benefits:

- Saves energy (up to 20–30%) by reducing HVAC and lighting equipment loads in either residential or commercial buildings
- Lowers sensor cost to under $10 per node compared to over $150
- Enables low-cost manufacturing of sensors and related components

Learn More:

- BTO Project Page
- Building America Solution Center

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7 Building Energy Modeling

Physics-based whole-building energy modeling supports building energy efficiency in a variety of ways. The most intuitive application of BEM is as the quantitative basis for holistic "integrated design" of energy-efficient new buildings and retrofits. The integrated design process is described in ASHRAE Standard 209, promoted by the American Institute of Architects (AIA) 2030 Commitment, recognized by certification programs like U.S. Green Building Council's LEED, and incentivized by a number of utility programs. The Rocky Mountain Institute's analysis "Reinventing Fire" estimates that BEM-driven integrated design can save between 8 and 16 quads, whereas BTO's own analysis, conducted using AIA 2030 and Scout, projects savings of between 2 and 6 quads, depending on adoption scenario.

Integrated design is the most direct mechanism by which BEM supports building energy efficiency. BEM is also used to rate the inherent performance of a building in a way that is independent of weather, occupancy, and operation. This is done by modeling the building under standard weather, occupancy, and operating assumptions and often by comparing that model to a model of the same building modified to minimally comply with code. This procedure is the basis of energy efficiency transactions such as code compliance, performance ratings and certificates, and federal, state, and utility incentives.

Finally, applied to prototype models, BEM is used to analyze entire building stocks at the portfolio, city, state, and national levels to inform the design of energy efficiency codes, products, programs, policy, and long-term strategic plans.

BTO's BEM R&D supports all BEM use cases with a portfolio that combines R&D with testing and validation, standards, and education. The program's research, standards, and outreach activities often leverage collaborations with organizations such as ASHRAE, AIA, and the International Building Performance Simulation Association (IBPSA).

An important element of the BEM sub-program that is somewhat unique within BTO's R&D portfolio is its support for the development of open-source BEM tools. BTO has historically developed BEM engines such as DOE-2, EnergyPlus™, and Spawn™. Spawn is a next-generation BEM engine that leverages equation-based modeling, dynamic simulation, co-simulation, and control specification standards to support both traditional BEM use cases and emerging use cases in control design, optimization, verification, and implementation.

Since 2012, BTO has also supported the development of the OpenStudio™ SDK, a middleware that provides a programmatic interface to EnergyPlus and facilitates the development of new energy modeling applications and services. This same programmatic interface is also the basis of OpenStudio's custom automation facility, which goes by the name Measures because its original and still dominant use case is performing systematic model transformations that correspond to the application of energy efficiency measures. Measures can be as simple as reducing lighting power density or as complex as applying the ASHRAE 90.1 Appendix G baseline transformation. Measures also supports large-scale analysis by simplifying the automatic and

systematic creation of a large number of model variants. Measures plays a central role in BTO's own large-scale analysis products and projects, including ComStock and Scout.

Over the past several years, BTO has pulled back on its development of user-facing applications and has increasingly relied on the private sector to build applications and services using EnergyPlus and OpenStudio. In addition to older EnergyPlus interfaces, such as DesignBuilder, AECOSim, and Simergy, recent years have seen a collection of new products or major features in existing products in both traditional and new market segments. A non-exhaustive list includes TRACE 3D Plus from Trane, Systems Analysis from Autodesk, Honeybee from Ladybug Tools, and Simulation Platform for Energy-Efficient Design (SPEED) from Perkins&Will. The success of this model has allowed BTO to focus its development resources on core capabilities, on expanding the applicability of BEM to new areas such as control design, district-system simulation, and hardware-in-the-loop testing, and to increasing its support for BEM-related codes and standards. In addition to EnergyPlus and OpenStudio, several BEM products funded via competitive mechanisms such as SBIR and BENEFIT have also been successfully commercialized. Spawn is a beta product and is not yet in commercial use.

In November 2020, BTO published a research and development opportunities for BEM document. This is a BTO-focused document that establishes BTO's priorities and is intended to act as the basis for ongoing dialogue between BTO and the BEM developer and user community. Some of the priorities identified include:

- Emphasis on both co-simulation and customization hooks as ways of expanding simulation scope in lieu of monolithic expansion of EnergyPlus
- Refactoring and re-engineering of existing code to facilitate a la carte reuse of key modules
- Support for both existing and new testing standards that cover a greater range of BEM capabilities and use cases with a new emphasis on regulatory, financial, and programmatic use cases that leverage deterministic model transformations
- Support for tool agnostic BEM education and training
- Collection and analysis of data to firmly establish and clearly communicate the value proposition of important use cases of BEM

7.1 EnergyPlusTM Whole Building Energy Modeling Engine

EnergyPlus™ is DOE's open-source BEM engine, designed to embody the state-of-the-art in BEM knowledge and techniques in a comprehensive and robust tool. Its detailed modeling features—sub-hourly time steps, radiative and convective heat transfer, air and moisture transfer, daylighting and shading, flexible component-level heating, ventilation, AC, refrigeration, and water heating configurations and controls—enable the evaluation of low-energy systems and designs and their impact on both energy use and indoor conditions.

DOE releases EnergyPlus updates twice a year. These include bug fixes and new features, as well as example files and full documentation. DOE uses regular surveys as well web engagement tools to gather, prioritize, and refine feature requests from end users and software vendors. One significant recent feature allows users to use python scripts to customize EnergyPlus behavior. EnergyPlus provides an application programming interface (API) that gives scripts-controlled access to internal state and features and then interprets these scripts at runtime at specific points in the simulation. This feature has already been used to implement advanced control, calculation of new metrics, and models for novel materials and equipment. EnergyPlus has also been refactored to better support co-simulation, with an immediate application in the Spawn (of EnergyPlus) BEM-controls engine.

An analysis of 1,112 completed projects submitted to the AIA 2030 Commitment program demonstrates that, relative to a Commercial Buildings Energy Consumption Survey 2003 baseline, buildings designed using EnergyPlus consume 20% less energy than buildings designed using no modeling. Extrapolated to new commercial construction, use of EnergyPlus for design has the potential to save 896 tBtu per year by 2030.

DOE's market strategy for BEM is to provide EnergyPlus along with the OpenStudio® SDK to facilitate third-party development of end user BEM applications and services that target different use cases and constituencies. EnergyPlus-based products introduced since 2016 include Autodesk's Systems Analysis, Trane's TRACE 3D Plus, Honeybee from Ladybug Tools, Cove.Tool from the company of the same name, and Climate Studio from Solemna, as well as in-house tools like Perkins&Will's SPEED. BTO has also recently migrated its Home Energy Score rating tool from DOE-2.1E to EnergyPlus. These join existing applications and services, including DesignBuilder, Simergy, Sefaira, and DOE's own Asset Score.

Technology History:

DOE has funded the development BEM engines since the 1970s. EnergyPlus follows previous engines Cal-ERDA, DOE-1, and DOE-2 and has been in continuous

Applications:

- Developing energy efficiency guidelines, codes, and standards;
- Designing new buildings, retrofits, and building control algorithms
- Calculating beyond code energy savings
- Demonstrating code compliance
- Continuous commissioning and fault detection in HVAC systems
- Model predictive control

Capabilities:

- Models building energy use for heating, cooling, ventilation, refrigeration, water heating, lighting, and plug loads

Benefits:

- When used to inform design, the use of EnergyPlus yields 20% improvement in predicted energy savings, with projections of 896 tBtus in potential annual savings by 2030.
- Benefits of other use cases have not been quantified; BTO is currently conducting an evaluation to quantify the benefits of BEM in code and program development.

Learn More:

- BTO Project Page
- 2018 BTO Peer Review
- BEM R&D Opportunities

development since 1997. The development team is led by the National Renewable Energy Laboratory (NREL) and includes other national labs (Lawrence Berkeley, Oak Ridge, and Pacific Northwest), as well as competitively solicited contractors from universities and private firms.

EnergyPlus was relicensed as open-source software in 2012 and was translated from FORTRAN to C++ in 2013. With help from OpenStudio®, EnergyPlus downloads have grown from just over 5,000 per version update in 2010 to over 50,000 in 2020.

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7.2 OpenStudio® Energy Modeling SDK

EnergyPlus is DOE's BEM engine. EnergyPlus has advanced capabilities, but also a detailed text-based interface that is cumbersome for both end users and third-party vendors who wish to embed EnergyPlus into applications.

To address this gap and spur EnergyPlus adoption, BTO and NREL developed the OpenStudio SDK, an open-source cross-platform collection of modules that can be combined in different ways to create different applications and analyses. The core module is the OpenStudio API, which allows developers to access EnergyPlus inputs and outputs programmatically—by calling methods on objects—rather than by reading and writing files, improving development productivity. The OpenStudio API also supports interoperability by supporting import from standard formats, including gbXML, BuildingSync, and HPXML.

The API enables one of OpenStudio's most unique and powerful features, Measures. OpenStudio Measures are small programs that can operate on OpenStudio models. Measures were first used to model transformation that corresponds to energy conservations, hence the name, but they have since been used to create custom reports and visualizations, perform quality assurance checks, and automate analysis workflows by connecting EnergyPlus to other tools. Nearly 400 Measures are now available on the Building Component Library. The OpenStudio-Standards gem is a collection of Measures and data tables for creating OpenStudio versions of DOE's commercial prototype building models and performing the ASHRAE 90.1 Appendix G "code baseline" transformation that is used in code compliance and LEED.

The final module is OpenStudio Server, which allows OpenStudio users to leverage the cloud for cost-effective high-throughput simulation by using Measures to define a large simulation space quickly and systematically. OpenStudio Server supports parametric analysis, uncertainty analysis, optimization, and calibration. Since 2016, several vendors have used the OpenStudio API to develop EnergyPlus applications, including Honeybee from Ladybug Tools, Systems Analysis from Autodesk, SPEED from Perkins&Will, and Cove.Tool from Cove.Tool. BTO itself uses OpenStudio Server along with the OpenStudio-Standards gem and other Measures to perform national and regional impact evaluations of multiple technologies to inform its technology portfolio investments.

Technology History:

OpenStudio began in 2008 as an EnergyPlus geometry creation plug-in for the 3D drawing tool SketchUp. It assumed its current strategic position and technical form in 2012. Originally, the OpenStudio project included a traditional graphical end-user application. However, after discussions with industry and IBPSA-USA, BTO stopped supporting and distributing the application in April 2020. OpenStudio is released twice a year, typically several weeks after the EnergyPlus release. The development team is led by NREL and includes other national labs (LBNL, ORNL, and PNNL), as well as competitively solicited contractors.

Applications:

- Used in BEM application development, process and workflow automation, and large-scale analysis, optimization, and calibration on local resources or the cloud

Capabilities:

- Open-source cross-platform collection of modules for BEM application development
- Flexible scripting facility "Measures" for task and workflow automation
- Cloud access for high-throughput simulation

Benefits:

- Rapid, low-cost development of new BEM applications and analyses
- Dynamic, shareable content and measures in the Building Component Library

Learn More:

- BTO Project Page
- 2018 Peer Review
- BEM R&D Opportunities

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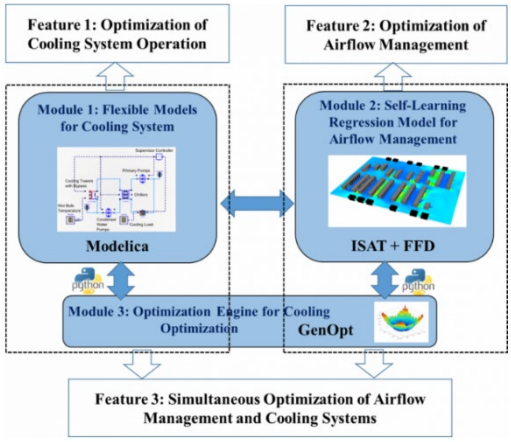
7.3 EcoStruxure™ IT Advisor CFD – A Data Center Toolkit to Manage Cooling and Airflow



Data Center Toolkit Module Diagram

Data centers in the United States use about 2% of the nation's electricity. As information technology (IT) equipment generates significant heat, half of this electricity is used for cooling alone. Data centers' cooling systems use non-traditional cooling designs and often face challenges in managing their cooling systems. The main challenge comes from the unique impacts of airflow. IT racks are not humans that must be kept comfortable, so data centers only cool their air intakes, not their exhausts. This results in in "hot aisles" and "cold aisles" in the data center, which creates airflow that can interfere with cooling. Early data center modeling programs focused on either data center room airflow management, or cooling system simulation, with models designed for limited and specific applications.

With funding from BTO, the University of Colorado-Boulder, in partnership with Schneider Electric and LBNL, developed the Data Center Toolkit, an open-source modeling platform that can be used to optimally manage data center cooling and airflow simultaneously. The Data Center Toolkit makes use of the Modelica Buildings Library (a free, open-source library with dynamic simulation models for buildings and district energy and control systems) for HVAC system simulation (Module 1). Along with this, it uses a fast fluid dynamics algorithm for airflow modeling (Module 2), and the GenOpt program for optimization (Module 3). In prototyping the Data Center Toolkit, the team worked with two data centers, one in Florida and one in Massachusetts. In doing so, they managed to achieve 53% energy savings in the Florida data center and 74% in the Massachusetts data center (well above the original predictions of 30%). Optimizing airflow and cooling separately would only provide about 27–46% savings.

Using technology from this project, Schneider Electric went on to develop EcoStruxure™ IT Advisor CFD (IT Advisor CFD for short), a cloud-based asset and planning software that enables data center managers to reduce operation expenses and plan for uptime, with analytics to facilitate capacity planning decisions. IT Advisor CFD is based off an older model, EcoStream, which did not include the Data Center Toolkit. Conventional technologies of the same nature can cost around $50k/year per license, while IT Advisor CFD costs only $6k/year per license.

Technology History:

Data Center Toolkit development began in October of 2016, with a planned ending date in November of 2019.The technology was commercialized in 2020. The IT Advisor CFD software was launched on the public site as a soft release on June 28, 2021, with a public release in September 2021.

Applications:

- Optimization of cooling energy in data centers

Capabilities:

- Optimization of cooling system operation
- Optimization of airflow management
- Can correctly pinpoint system deficiencies, suggest improvements, and estimate savings that would result from improvements

Benefits:

- Improves efficiency of data center cooling systems with average energy savings of 50–70%
- Product is updated frequently via the web
- Lowers cost to operate and maintain data centers

Learn More:

- BTO Project Page
- BTO Success Story

Contact

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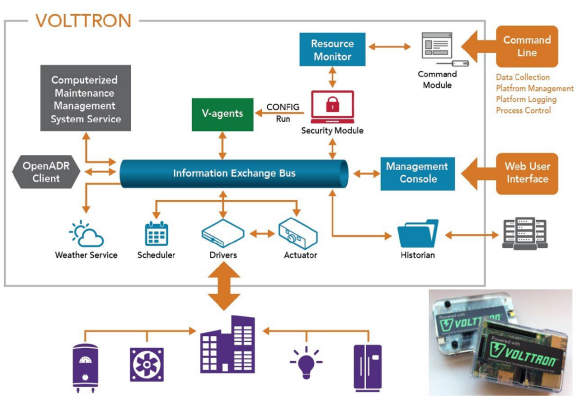
7.4 VOLTTRON™: Automated Economic Dispatch for Building-Integrated Combined Cooling, Heating, and Power (CCHP) Systems



VOLTTRON™: Optimal Economic Dispatch for Integrated Energy Systems

CCHP systems have efficiency and cost-effectiveness benefits for large buildings and campuses. However, the lack of an integrated dispatch and control solution for these systems prevents their economic benefits from being realized.

With support from the Building Technologies Office, Pacific Northwest National Laboratory—in partnership with Arizona State University, Washington State University, and Frontier Energy—developed an automated economic dispatch algorithm for CCHP systems that allows building operators/owners to make "optimal" decisions about the operation of their CCHP using price signals, monitored performance data, a model of their building's performance (either physics-based or empirical), and their risk preferences.

The automated Economic Dispatch algorithm has been implemented as open-source software for the VOLTTRON™ platform. VOLTTRON is an open-source and cyber-secure IoT platform for building and DER monitoring and control applications. VOLTTRON supports deployment of software for managing building systems, like heating and air-conditioning, and DERs, like electric vehicle charging stations and PV arrays, and their interactions with one another and the grid. VOLTTRON is deployable on low-cost computing resources and can communicate with equipment and systems that support any number of industry standard communication protocols. Multiple VOLTTRON instances can communicate with one another to coordinate control among multiple buildings in a neighborhood or campus.

VOLTTRON and its applications are hosted on the Eclipse VOLTTRON™ site.

Technology History:

The automated economic dispatch algorithm and its implementation were developed as part of DOE's Grid Modernization Laboratory Consortium. In 2018, the VOLTTRON™ system was successfully deployed in Utica, NY, at Burrstone Energy Corporation's CCHP plant, and the Economic Dispatch algorithm was successfully field-tested. Frontier Energy has since adopted the Economic Dispatch tool for its customers.

Applications:

- Cost-effective economic dispatch of building-integrated CCHP systems

Capabilities:

- Open-source software that can be deployed using low-cost (<$200) computing resources or the Cloud
- Enables adoption of building integrated CCHP systems, minimizing operational cost and maximizing return on investment

Benefits:

- Improves energy efficiency in buildings
- Improves grid reliability, resilience, and renewables integration
- Savings on the order of $20,000 per year for a CCHP operator
- Potential energy savings is about 2 to 3 quads

Learn More:

- BTO Project Page
- 2018 BTO Peer Review

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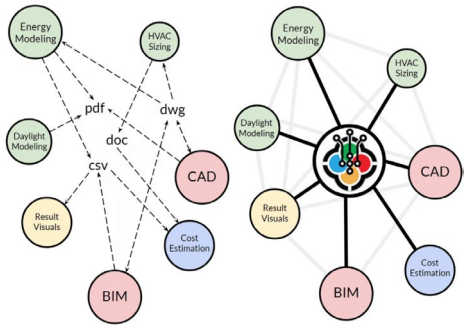
7.5 Ladybug Tools: CAD-Integrated Web-Based Building Performance Simulation Platform



Ladybug Tools Pollination Connectivity of Numerous CAD-based Software Platforms

Building performance simulation (BPS) has matured over several decades with combined efforts between academia, government, and industry. BPS provides quantitative estimates of building energy use that can be used to inform and optimize building design. Lack of efficient interoperability between design software and BPS software makes using BPS in design more challenging than it needs to be and impedes collaboration between designers and BPS experts.

Ladybug Tools LLC, most notable for its suite of open-source BPS plug-ins with insect names (the eponymous Ladybug, Honeybee, Butterfly, and Dragonfly), has created a new product, Pollination, with a new approach to integrating BPS in design. Developed with the support from the BTO in the form of an SBIR award, Pollination isn't a centralized "one-stop-shop" tool, but rather an ecosystem. Pollination is a web-based collaboration hub backed by cloud computing resources that uses plug-ins to connect to existing CAD/building information modeling (BIM) software. Pollination essentially takes a designer's native design tool and uses the cloud to turn it into a collaborative BPS tool via which design teams can collaborate with BPS experts.

An important innovation of the Pollination ecosystem is the notion of a "recipe." A recipe is a script, a set of steps, that defines a particular BPS analysis. Recipes embody and encode expertise about design and BPS workflows. Pollination uses recipes to foster collaboration between designers and BPS experts. Recipes are typically written by BPS experts, but once written, they can be used by anyone. Pollination includes a library of ready-made recipes for common analyses. BPS experts and designers can use existing recipes or develop new ones that they can share within the project group or the larger Pollination community.

Pollination also has other unique features such as a cloud-first but not cloud-only approach. Users can save money and resources by utilizing cloud computing resources at their discretion and only when the scale of a project requires it.

By improving interoperability for modeling tools, end-to-end collaboration, and automation at scale, Pollination gives design teams the freedom to innovate.

Technology History:

Ladybug Tools development began in 2013, with various software releases over a period of five years, including the eponymous Ladybug, Honeybee, Dragonfly, and Butterfly plug-ins for Grasshopper in Rhino3D. In 2018, Ladybug Tools LLC was formed, and with it, the development of Pollination started. Pollination began early user access in 2021.

Applications:

- A web-based platform with plug-ins for multiple CAD/BIM software packages that turn those packages into collaborative BPS tools

Capabilities:

- Plug-ins for Revit, Rhino, and Grasshopper
- Integrated support for simulation on both local resources and the cloud
- Supports multiple BPS tools: EnergyPlus, OpenStudio, Radiance, and LadyBug Tools
- Provides verified simulation recipes for typical workflows, which can be customized
- Streamlines cross-disciplinary collaboration between architects, engineers, and BPS experts

Benefits:

- Real-time collaboration throughout the entire project saves time and enables informed design modifications or changes
- User-friendly limited public API allows access to multiple BPS engines and development of custom applications
- Free or subscription service options to suit individual or organization requirements

Learn More:

- BTO Project Page
- Pollination

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Appendix A – Summary of Commercialized Solid-State Lighting Technologies 2015–2020

Manufacturer	Technology name	Product type (I.e., component, material)	Number of product offerings	Description	Initial commercialization
Philips Lumileds Lighting, LLC	LED chip	LED Component	5	Development and industrialization of InGaN/GaN LEDs on patterned sapphire substrates for low-cost emitter architecture	2015
Lumileds	LED architecture	Light Engine	5	High-voltage LED light engine with integrated driver	2016
Pixelligent Technologies LLC	Nanomaterial	Material	2	Nanomaterial additive for improved light extraction	2017
Lumileds	LUXEON MX	LED Component	12	130 LPW 1000 LM warm white LED for illumination	2017
Lumileds	LUXEON V	LED Component	7	Development and industrialization of InGaN/GaN LEDs on patterned sapphire substrates for low-cost emitter architecture	2017
Lumileds	LUXEON C Cyan	LED Component	1	Improved InGaN LED system efficacy and cost via droop reduction	2017
Lumileds	LUXEON C Green	LED Component	1	Improved InGaN LED system efficacy and cost via droop reduction	2017
Lumileds	Rebel Color	LED	4	Improved InGaN LED system	2017

Manufacturer	Technology name	Product type (i.e., component, material)	Number of product offerings	Description	Initial commercialization
	Cyan	Component		efficacy and cost via droop reduction	
Lumileds	Rebel Color Green	LED Component	3	Improved InGaN LED system efficacy and cost via droop reduction	2017
Lumileds	Z Color Green	LED Component	4	Improved InGaN LED system efficacy and cost via droop reduction	2017
Lumileds	Z Color Cyan	LED Component	3	Improved InGaN LED system efficacy and cost via droop reduction	2017
RTI/Finelite	Tunable Light	Lighting Product	1	Color-tunable light	2017
OLEDWorks	OLED Panel	OLED Component	12	High performance OLED panel and luminaire	2018
Lumileds	Luxeon V2	LED Component	4	High-efficacy high-power LED for directional applications	2018
Lumileds	Luxeon CZ Cyan	LED Component	4	Improved InGaN LED system efficacy and cost via droop reduction	2018
Lumileds	Luxeon CZ Green	LED Component	4	Improved InGaN LED system efficacy and cost via droop reduction	2018
RTI/Finelite	App	Controls	1	Light controller interface	2020
RTI/Finelite	Control Packs	Controls	2	Light power supply	2020
RTI/Finelite	Control Station	Controls	1	Control hub	2020
Lucent Optics	Waveguide	Optic	20	Light diffusing	2020

Manufacturer	Technology name	Product type (i.e., component, material)	Number of product offerings	Description	Initial commercialization
				optic	
Lucent Optics	Light Engine	Light Engine	1	Light engine	2020
Pixelligent Technologies LLC	Materials	LED Material	2	Nanomaterial additive for light extraction efficiency	2020
OLEDWorks	Lumicurve wave	OLED Component	2	OLED panel	2020
TOTAL			**101**		

Appendix B – Additional Technology Highlights

The Buildings Technology Office (BTO) chose to spotlight 23 technologies in the main body of the report, seeking to equally represent technologies from across its Emerging Technologies program areas. This appendix includes additional one-page technology profiles that highlight commercial products developed from BTO funding; inclusion in the Appendix, compared to the main body of the report, should not be considered dissatisfaction or disfavor of the technologies that follow, nor should inclusion in the main body of the report be considered an endorsement of the highlighted products.

B.1 QwikSEER+® and QwikSwap®: Two Energy-Saving HVAC Control Systems

Mainstream's QwikSEER+ WattSaver and QwikSwap Products

Existing heating, ventilating, and air-conditioning (HVAC) systems typically have inefficient, oversized blower motors, which draw excess power and add heat to the cooled air circulating throughout the building. Technicians often set these blowers at high speeds to ensure continued air movement in less-than-ideal ducts and minimize coil freeze-ups due to low airflow.

With funding from BTO, Mainstream Engineering Corporation developed a pair of electronic control systems that can be retrofitted into almost any residential or light commercial HVAC system to reduce the blower motor inefficiency. Both QwikSEER+™ and QwikSwap® are easily installable electronic control boards that are directly wired to the blower motor. The electrical control system's sensors enable the evaporator airflow to be continuously and automatically adjusted, decreasing power use. An optional humidity sensor can be added so that the blower speed can also be optimized to reduce the structure's humidity. This technology works with new and existing AC units that are equipped with low-cost permanent split capacitor motors, achieving increased efficiencies without investing in expensive electronically commutated motors.

QwikSEER+™ and QwikSwap® provide cost-effective efficiency solutions for most conventional air-conditioning (AC) systems. The control board, when installed, can boost an air conditioner's energy efficiency by 7%–13% and increase the humidity removal rate.

Both products are available worldwide from HVAC distributors. In 2018, Mainstream Engineering partnered with Motors & Armatures, Inc., a well-known company in the field of electronically commutated motors. Motors & Armatures chose QwikSwap™ to enhance its Azure® motor. Motors & Armatures's branded kit, QwikSwap™Azure®, is available from the Motors & Armatures website.

Technology History:

The QwikSEER+™ and QwikSwap® technologies were developed by Mainstream Engineering Corporation with assistance from BTO American Reinvestment and Recovery Act funding and SBIR grants. They were both commercialized in 2013. Mainstream Engineering has patented both QwikSEER+™ (2015) and QwikSwap® (2016–2020).

Applications:

- Residential and commercial HVAC systems to maximize system efficiency and improve summertime humidity conditions

Capabilities:

- Improves EER by 7.5–13.0 % (0.7–1.5 points)
- Allows automated, continuous adjustment of evaporator airflow to reduce power consumption
- Allows conversion of single speed to variable speed blower motor operation and control

Benefits:

- Affordable alternative for variable speed blower motor operation when compared to ECM blower motors
- Provides energy savings up to 13% during periods of high demand and increased humidity removal
- Universal retrofit for HVAC systems, no programming required
- Eliminates the need for technicians to maintain a large inventory of multiple ECM motor variations

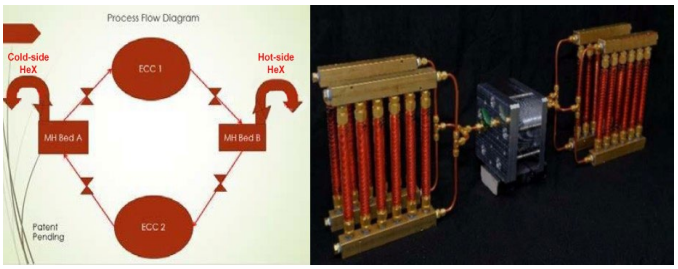
Learn More:

- QwikSeer™
- QwikSwap™

Contact:

Mainstream Engineering Corporation
200 Yellow Place
Rockledge, FL 32955
www.mainstream-engr.com

B.2 Hydrogen/Metal Hydride Based Heat Pump System for Large HVAC Applications Utilizing an Ionic Liquid Desiccant Subsystem



Schematic of electro-chemical compressor and metal–hydride system (LHS) and Xergy's ECC-MHX (RHS)

In the United States, HVAC systems today represent the largest energy end use in buildings, accounting for nearly 15 quads of primary energy use annually, or about 38% of all energy consumed in U.S. residential and commercial buildings each year (EIA 2021).

With support from the BTO, Xergy and its partners—Haier, the University of Delaware, the National Renewable Energy Laboratory, and Oak Ridge National Laboratory (ORNL)—developed a higher-efficiency HVAC system that encompasses electrochemical compression, metal hydride heat exchangers, and ionic liquid systems for improved efficiency compared to conventional vapor compression HVAC systems.

The efficiency gains are from the physical characteristics of the individual components used. The electrochemical compressor is a solid-state technology (no moving parts) that is vibration free, modular, and scalable for compressing working fluids. The metal hydride heat exchanger provides a higher thermal exchange efficiency with a reduced volume (footprint) over a wider temperature range. Lastly, the ionic liquid desiccants can use both the energy from latent cooling in removing moisture and the waste heat energy from sensible cooling for regeneration (dehumidification) of the desiccant. This system does not use traditional mechanical compression or traditional HFCs, which are hazardous and have higher global warming potential (GWP).

Xergy's HVAC system features a net energy improvement of 20% compared to conventional vapor compression HVAC systems. For an average building size (15,000 ft^2), an improvement of 20% in HVAC efficiency would reduce annual operating cost by $2,000. Currently, Xergy has developed six commercial product platforms resulting from its research, including advanced materials for electrochemical applications, advanced materials for water permeation, electrochemical devices (based on these materials), ionic liquid (desiccants), metal hydride systems, and devices for climate control.

Technology History:

Xergy Inc. formed in 2010 to leverage its experience in fuel cell membranes to develop climate control technologies such as refrigeration and AC. In 2015, the BTO funded Xergy to develop an electrochemical compressor combined with a metal hydride heat exchanger system for HVAC applications. Xergy's metal hydride technology is now poised to serve the needs of ultra-low refrigeration and hydrogen compression applications, given the low GWP nature of its solid-state heat pump technology. Xergy was recently acquired by Fortescue Future Industries.

Applications:

- Applicable to HVAC applications, including window AC units

Capabilities:

- HVAC system operates without GWP working fluids, e.g., O_2, Water, carbon dioxide (CO_2), NH_3, and H_2
- Achieves >20% efficiency compared to conventional vapor compression-based HVAC system
- System components are modular and scalable to fit building HVAC sizing requirements
- System contains no moving parts

Benefits:

- System provides low maintenance, noiseless, and vibration free operation
- Eliminates the use of hazardous and high GWP HFCs as refrigerant by using "green" refrigerants
- Technology platforms developed for this program have resulted in the commercial launch of over 1,000 new products

Learn More:

- BTO Project Page
- 2019 Peer Review

Contact:

Fortescue Metals Group Ltd
Level 2 87 Adelaide Terrace
East Perth WA 6004
Australia
https://www.fmgl.com.au/

B.3 Fuel-Fired, Multifunction Heat Pump

ORNL's Prototype Fuel-Fired, Multifunction Heat Pump

HVAC equipment for residential buildings consumes approximately 50% of total residential energy consumption in the United States. Space heating is the dominant component, accounting for 43% of total energy consumption, followed by water heating at 19% and space cooling at 8%. Natural gas-fired furnaces and boilers are the most common heating systems. If the coefficient of performance (COP) for this HVAC and water heating technology could be improved, energy efficiency could significantly increase.

Oak Ridge National Laboratory (ORNL), with assistance from BTO, and industry partners Southwest Gas and IntelliChoice Energy, have developed a residential, fuel-fired, multifunction heat pump (FFMHP) that achieves high source energy efficiency for space conditioning and water heating. The FFMHP is similar to traditional heat pump units but with two main differences. First, natural gas is used to supply shaft power to the compressor. Based on a site versus source comparison, it was found that this would result in higher primary energy savings than using an electric motor. Second, waste heat is recovered from the engine to supplement space and water heating and to reduce the energy input. The recovered waste heat is applied to the refrigerant during the heating season and to water during the cooling season. The system is controlled by a printed circuit board (PCB) system control module that determines how much waste heat is allocated when both space and water heating are required, based on the predetermined settings stored in the PCB's memory. The PCB controls the compressor and fan speeds and allows the multifunction HVAC system and building demand to be monitored.

Technology History:

ORNL and industry partners, Southwest Gas and Blue Mountain Energy (BME), began development on the FFMHP in 2010. Prototype units were fabricated by Southwest Gas using an engine provided by Marathon Engine Systems and sent to ORNL for testing. From 2010–2014, many prototype units were constructed and tested, both in the laboratory and the field, to evaluate performance, optimize cooling and heating capabilities, improve efficiency, and replace components to reduce the overall unit cost. In 2015, a residential scale version of the FFMHP, ready for commercialization, was developed with an optimized footprint, electric consumption, and energy efficiency. Currently, the FFMHP is available from BME.

Applications:

- Production of a natural gas fueled multifunction heat pump that can be used as an alternative to electric heat pumps and gas furnaces in residential heating and cooling applications

Capabilities:

- Provides 2 to 5 tons of cooling capacity
- Achieves a cooling COP of 1.3 at an ambient temperature of 95°F and a heating COP of 1.5 at 47°F
- Provides low ambient heating by recovering waste heat from fuel combustion
- Provides 60 gallons per day of domestic hot water at 140°F from waste heat recovery
- Provides variable-capacity operation to meet user demand

Benefits:

- Reduces primary energy usage by recovering waste heat to supplement heating and produce hot water
- Can be retrofitted into existing residential applications or added into new residential installations

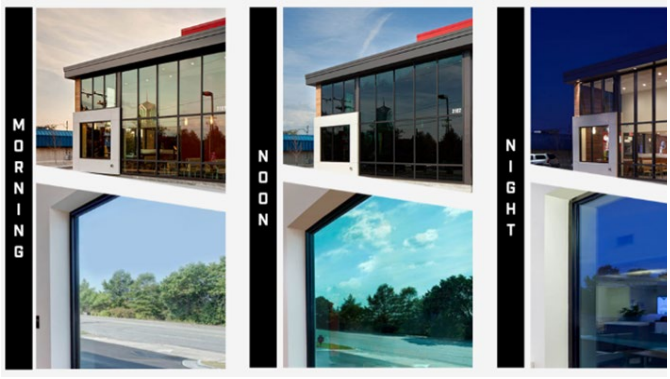
Learn More:

- BTO Project Page
- 2014 Peer Review

Contact

Blue Mountain Energy
2949 W. Lakeland Blvd.
Las Vegas, NV 89032
bluemountainenergy.com

B.4 Suntuitive™: Sunlight-Responsive Thermochromic Window Systems



Pleotint's Suntuitive™ Thermochromic Dynamic Glass

In 2010, space heating, cooling, and lighting services made up 56% of the energy consumed by commercial and residential buildings. The amount of energy consumed for heating and cooling depends on a building's insulative properties, which include the windows. For a number of years, there has been a potential market for variable tint, energy-control windows with acceptable cost, performance, and durability characteristics. Fixed tint windows are a compromise between how much light and solar heat gain is allowed to enter a building. Research has focused on developing window technologies with additional features that reduce or enhance the effects of solar heat gain, prevent sunlight glare, and are compatible with daylighting schemes.

With support from BTO, Pleotint, LLC, tested, developed, and commercialized the Suntuitive™ sunlight-responsive thermochromic (SRT) window system, a high performance window with dynamic sunlight controls, a high insulation value, and low solar heat gain. Pleotint's SRT window is dynamic because it reversibly changes light transmission throughout the day based on the heat provided by the sun. Every day of the year, every time of the day, and on every orientation on a building, the windows tint according to the sun's intensity without using wires, power supplies, or controls. This allows the windows to optimize the incoming brightness and heat load in buildings. The interlayer is where the thermochromic elements are embedded, and it is made of the most common safety glass lamination polymer, polyvinyl butyral, which can be produced in rolls and shipped to certified partner window fabricators throughout the world. This allows dynamic windows to be manufactured almost anywhere safety glass laminates are produced.

Technology History:

Suntuitive™ was developed and commercialized in 2011 by Pleotint, LLC and is installed at over 500 locations worldwide.

Applications:

- Can be used in retrofit, replacement, and new construction of both commercial and residential applications to control daylighting and reduce energy consumption

Capabilities:

- Optimizes daylighting and provides visible light transmission between 50% and 10%
- Achieves solar heat gain coefficient as low as 0.11
- Provides dynamic window tinting without wires, power supplies, or controls
- Provides a thermochromic interlayer that can be supplied to laminators and window manufacturers worldwide

Benefits:

- Blocks 99% of harmful ultraviolet (UV) light
- Provides sound reduction and impact resistance, decreases glare, and minimizes fading from solar UV radiation without compromising visibility
- Achieves 20%–43% annual energy savings depending on climate, based on a Lawrence Berkeley National Laboratory (LBNL) study
- Installs like any conventional glazing without special requirements
- Less energy consumption means less pollution through energy production

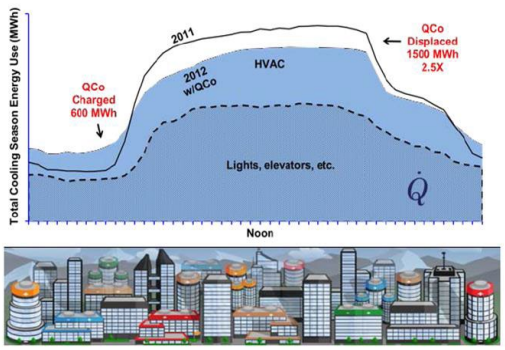
Learn More:

- BTO News Article

Contact

Pleotint, LLC
7705 West Olive Road West Olive, MI 49460
www.suntuitive.com

B.5 Predictive Control Harnesses Building Thermal Mass as High Performance Energy Storage



QCoefficient's Energy Displacement Data for Willis Tower

In the United States, HVAC systems use 44% of the total energy used in buildings, primarily during the summer.[11] HVAC system efficiencies systems have improved over the last several decades, but methods to manage energy demand have not been realized until recently.

One effective technique uses thermal energy storage (TES) in combination with passive and/or active strategies to shift all or a portion of a building's cooling energy draw to off-peak hours when electricity prices and carbon emissions are lower.

QCoefficient, Inc. (QCo) and the University of Colorado, with assistance from the BTO, have developed a system that can utilize the thermal mass in a large commercial building—from the foundation to the furniture—as a TES medium to dynamically reshape its cooling load profiles. QCo gathers information about the building's energy assets—its size, structural materials, envelope characteristics, and occupancy, as well as the efficiency of its existing HVAC system under load—and uses it to create an EnergyPlus model of that building. That model is then used in an optimization framework, which also takes electricity prices and short-term weather forecasts, to devise an optimal TES/HVAC control strategy for the following day. This strategy re-schedules the building's cooling energy use into non-peak times for utility rate negotiation. Importantly, it also does not compromise occupant comfort.

QCo's algorithm has been applied to old and new (LEED Gold certified) building designs with positive results. QCo's payback varies by regional electricity rates. In New York City, which has the highest electricity rates in the United States, a 20% reduction in electricity consumption equates to a payback of less than one month.

Technology History:

QCo commercialized the technology in 2012. It has been demonstrated in several large commercial buildings in downtown Chicago and New York City. QCo is commercially deploying the technology through sales channel partners in several other large U.S. cities. By 2022, QCo expects to have approximately 10 million ft^2 of floor space under contract. QCo has planned expansions in Atlanta, Boston, and New York City, where it continues to operate a 1.3 million ft^2 LEED Gold high rise building in midtown Manhattan.

QCo is also working on a predictive control and grid-interactive efficient

Applications:

- Offers large-scale energy and demand management for utilities, grid operators, and building managers in commercial, campus, shopping mall, mixed use, and airport sectors

Capabilities:

- Optimizes large commercial building cooling operations via automated, cloud-based control
- Optimizes and coordinates a portfolio of such buildings, creating an energy asset in grid-congested urban markets
- Targeted operation improves and accommodates occupant comfort
- Achieves rapid deployment, within 4 weeks
- No permitting required
- No capital equipment cost
- Reduced carbon emissions regulation ready (e.g., NYC LL97)

Benefits:

- Reduces site energy expense by 20–40%
- 1–2 month payback (regional utility rate dependent) by reducing energy cost with low installation and operating expenses
- Reduces greenhouse gas (GHG) emissions by reducing and shifting daytime energy use to the night
- Improves grid efficiency and operation by reducing congestion and shifting demand to more efficient baseload plants

Learn More:

- BTO Success Story

[11] 2012 CBECS (Table E1) Survey Data, U.S, Energy Information Administration

buildings project funded by U.S. Dept. of Energy EERE office programs.

Contact

QCoefficient, Inc.
310 South Michigan Avenue #903
Chicago, IL 60604
www.buildingsasbatteries.com

B.6 OpenADR Client: Distributed Intelligent Automated Demand Response (DIADR) Building Management System

Siemens OpenADR Client

Demand-side energy management strategies present an opportunity to improve energy efficiency in buildings across the nation. Consumers tend to use energy at the same time and in similar ways. During times where demand for energy is especially high, extra power plants are needed to meet this demand. These plants often end up being more costly to operate, and they create more GHGs. DR, especially automated demand response (ADR), is a method to improve the efficiency of the whole electrical power grid, which can offer significant economic and environmental benefits. DR is a set of actions taken to reduce load when the electric grid's supply-demand balance is at risk of disparity or when market conditions raise electricity costs. ADR automatically signals from a utility or Independent System Operator (ISO)/ Regional Transmission Organization (RTO) to connect, in real-time, with its customers' end use control systems and strategies. ADR technology is key to realizing sufficient DR adoption rates. OpenADR can provide a unified platform to help utilities and consumers manage the constantly changing collection of DERs, unifying a system of systems.

Essentially, the OpenADR Client communicates with a demand response automation server, per standard protocol, to send information and signals to switch electrical power-using devices off in periods of high demand. This highly flexible infrastructure facilitates the automation of customer and third-party responses to various DR programs and dynamic pricing, so that utilities, ISOs, energy and facility managers, aggregators, and hardware and software manufacturers can optimize the energy system's performance.

With support from the BTO, the University of California Berkeley, LBNL, and Siemens Corporation collaboratively demonstrated a DIADR server that reduced peak loads by 30% at a building on Berkeley's campus run by Siemens Apogee Insight building automation system. Utilizing the OpenADR protocol developed by LBNL, the team integrated an ADR system with a Siemens Smart Energy Box, which provided supervisory control and comprehensive demand-side energy management for lighting, plug load, and HVAC systems.

Technology History:

Siemens' OpenADR Client was developed and validated by Siemens Corporation, Corporate Technology, UC Berkeley, and LBNL with support from BTO. It was commercialized in 2011 by Siemens Building Technologies. An OpenADR Alliance was formed by industry stakeholders to build on the foundations of technical activities and ultimately facilitate widespread adoption of the OpenADR standard throughout the energy industry. At the end of 2018, the OpenADR 2.0 IEC standard was established, and it validates the global importance of the OpenADR specification.

Applications:

- Facilitates automated DR to reduce peak load on the power grid

Capabilities:

- Enables automated building DR
- Provides information exchange between building automation systems and utilities or ISO
- Agent-based control network for central and distributed load controls

Benefits:

- Achieves up to 30% peak load savings in commercial buildings
- Improves power grid efficiency through ADR
- Enables utility rebate qualification for commercial buildings and provides a 5-year payback
- OpenADR communication can easily be integrated into new and existing Python projects with use of OpenLEADR Python package

Learn More:

- To date, several OpenADR certified products from Siemens and other vendors are available on the market (see list)

Contact

Siemens Corporation
755 College Road East
Princeton, NJ 08540
www.siemens.com/us/en

B.7 Quiet Climate 2: Efficient Heat Pump for Classrooms

Bard's Efficient Heat Pumps for Classrooms

The HVAC needs of most schools have historically been met by large, centralized systems that use boilers to generate steam or hot water for heating and chillers to generate chilled water for cooling. These centralized systems have several drawbacks, such as high installation costs, complex maintenance requirements, and difficulty providing individualized climate control to classrooms. Additionally, these systems often have low energy efficiency and produce excessive acoustic noise, making learning environments less enjoyable, productive, and efficient.

With assistance from the BTO, LBNL and Bard Manufacturing Company Inc. developed a packaged heat pump that offers schools an alternative to centralized systems. Known as the Quiet Climate 2 CH-Series, the unit is an improved version of the original Quiet Climate model developed by Bard in the late 1990s. The Quiet Climate 2 uses a built-in sound-reducing plenum to achieve operation at an audible noise level of ≤ 42 dB, and it can be fitted with additional accessories (sound/vibration curbs and supply/return air acoustical plenums) to further reduce noise levels. The decentralized HVAC approach also minimizes the impact of repair and replacement. When a centralized system fails, the entire school suffers. If a Quiet Climate unit requires maintenance or replacement, only a single classroom is inconvenienced.

In July 2011, Bard introduced the next-generation model in the Quiet Climate product line: the TS-Series, and in 2013, Bard enhanced it even further with the new CH-Series. This new model is more efficient and provides greater cooling/heating capacity than the CH-Series original QC2 while maintaining the same quiet operation with the utilization of Bard's sound accessories.

Technology History:

Quiet Climate 2 technology was developed by LBNL and Bard Manufacturing Company Inc. and commercialized in 2008 by Bard. Currently, over 1,000 CH-Series units are being used in schools throughout the United States.

Applications:

- Used to provide quiet, energy-efficient space conditioning and improved air quality

Capabilities:

- Provides 2.5 to 5 tons of cooling/heating capacity with an integrated part-load value of up to 15.0
- Up to 3.5 COP heating efficiency

Benefits:

- Reduces HVAC expenses by more efficient operation
- Provides quiet operation
- Allows more classroom space to be utilized for educational purposes, due to having a smaller footprint than traditional central HVAC systems

Learn More:

- Heat Pump Systems
- Improving Indoor Air Quality for Safer Schools
- Case Studies

Contact

Bard Manufacturing Company, Inc.
1914 Randolph Drive, P.O. Box 607
Bryan, Ohio 43506
Website: http://www.bardhvac.com/

B.8 Smart Energy Load Control Module: CEA 2045 Compliant Wireless Controller for Water Heaters

Emerson's Smart Energy Load Control Module

Water heating is the second largest energy use in residential homes, accounting for roughly 13% of all residential building energy consumption, according to EIA. Newer, high-efficiency electric water heaters offer energy savings and the potential to lower peak electricity demand when power utilities are forced to bring their oldest and costliest plants online. Often, these plants have higher emissions due to lower efficiencies and the use of natural gas as fuel.

Emerson Electric Co., with American Recovery and Reinvestment Act funding from the BTO, developed a load control switch designed for electric water heaters. This new technology is a CEA-2045 compliant wireless controller for water heaters that integrates directly into a residential, smart energy home network. It is one of the first products to comply with the CEA-2045 standard, which was developed to ensure the ease of utility-to appliance connectivity. Once the remote-control switch is installed, the controlling utility can set it to turn on or off via schedules, price signals, or homeowner preferences.

Emerson's water heater technology combines smart grid and load switching technologies to smooth peak power demands and absorb sudden renewable energy power surges when the wind blows or the sun shines. Its "smart" operation enables communication between utility companies, the smart grid, and household appliances to improve energy efficiency and help consumers manage their home's energy consumption nearly in real-time. Smart grid-ready appliances can respond to external data and control signal inputs like power utility pricing information, and they can turn off all or part of the peak demand period with no inconvenience or impact on the home occupants.

Technology History:

This technology was developed by Emerson Electric Co. It was commercialized in 2013. Currently, Emerson Electric is evaluating the market and working with utilities to offer the Smart Energy Load Control Module as part of DR pilot programs.

Applications:

- This product can be used in residential and light commercial electric water heating applications

Capabilities:

- Achieves compliance with CEA-2045 communication standard
- Accepts various communications modules, including ZigBee, Wi-Fi, FM, RDS, and cellular services
- Enables wireless temperature sensing
- Provides connectivity to the smart energy home area network
- Provides standard electric water heater control and enables "grid smart" capability

Benefits:

- Provides connectivity to the smart energy home area network
- Offers significant peak demand savings by automatically moving demand from the grid from peak hours to off-peak hours

Contact

Emerson Electric Co.
8000 W Florissant Ave., #4100
St. Louis, MO 63136
www.emerson.com

B.9 Trilogy® 45 Q-Mode® (QE) Ground-Source Integrated Heat Pump

ClimateMaster's Trilogy® 45 Q-Mode® (QE)

Traditional heating, cooling, and water heating systems for commercial and residential buildings operate independently and require large energy inputs to keep spaces comfortable. Most cooling and heating systems today operate at fixed speeds, which cause large spikes in energy use. Increasing the energy efficiency of heating, cooling, and water heating systems will significantly lessen these spikes in energy consumption and decrease utility bills for homes and commercial buildings.

With assistance from the BTO, ORNL developed a variable-capacity ground source integrated heat pump (GS-IHP) in 2007. The GS-IHP uses geothermal energy via a ground heat exchanger, which consists of piping buried in horizontal or vertical loops installed in the ground. The unit provides heating, cooling, water heating, and dehumidifying services to a home in a single combined system, drastically decreasing energy consumption and peak electricity demand. ClimateMaster, Inc. developed the Trilogy 45 Q-Mode during a collaborative project with ORNL to evaluate its performance. It recovers waste heat from its space cooling and dehumidification processes to heat water, which reduces the overall purchased energy for the building. Repurposing the waste heat also serves to lessen the load on the ground heat exchanger. The Trilogy 45 incorporates three variable speed technologies (compressor, indoor blower, and circulation pumps) to keep the building comfortable while using less energy.

Trilogy® 45 Q-Mode® (QE) has demonstrated an energy efficiency ratio (EER) rating of 45, the highest ever achieved at the time of its market introduction in 2012. ENERGY STAR® designated it as one of the most efficient certified products in 2020 with a COP of 5.1. Based on ENERGY STAR projections, the unit will save users up to 69% above the federal minimum performance standard and provide the lowest operating costs on the market.

Technology History:

The Trilogy® 45 Q-Mode® (QE) was developed by ClimateMaster, Inc. in collaboration with ORNL as part of a U.S.-China Clean Energy Research Center project to accelerate ground source heat pump deployment. The technology was commercialized in 2012. ClimateMaster is a leading water-source heat pump manufacturer in North America. It has won numerous awards for the Trilogy® 45 Q-Mode® (QE), including three in 2013 (the International R&D Award for Innovation, the AHR Expo Innovation Award, and an R&D 100 Award) as well as the ACHR NEWS Dealer Design Gold Award in 2012.

Applications:

- A high-efficiency ground source integrated heat pump that can be used in new or retrofit residential and small commercial building applications

Capabilities:

- Provides the same space heating and cooling capacity as conventional heat pump systems in addition to water heating and humidity control
- Coefficient of performance of 5.1
- Over 70% peak demand savings, depending on the location
- Access and control of unit available over the internet using iGate Connect thermostat, a Wi-Fi-enabled, communicating, programmable thermostat

Benefits:

- Cost savings, 69% annual energy savings compared to minimum efficiency HVAC
- Year-round Q-Mode operation can offer energy savings of over 80% for water heating, and can provide free air-conditioning in the summer months
- Reduces electricity consumption and peak demand by operating at less than full capacity and recovering waste heat
- Ground-source heat pumps provide efficiencies of 400 to 500% (for every unit of electricity put into a ground source heat pump, 4 to 5 units of heating and cooling are returned)

Learn More:

- BTO Success Article (2013)

Contact

ClimateMaster, Inc.
7300 S.W. 44th Street Oklahoma City, OK 73179
www.climatemaster.com

B.10 ThermaDeck®: An Insulated and Ventilated Roof System

ThermaDeck® Roofing System Controls Radiation, Convection, and has Insulation to Provide Conduction Resistance to Heat Transfer

Multiple problems exist with today's composition roofs found on most homes across the United States. Made from an asphalt-based material, they conduct the sun's heat extremely well and reach temperatures from 150° to 185° F. This heat crosses through the roof decks and into the attic space below, warming air conditioner (AC) ducts and decreasing the efficiency of the AC system.

Billy Ellis Roofing LLC designed the ThermaDeck® roofing system to address heat buildup caused by conduction, convection, and radiant heating that increases cooling costs. The technology uses a passive, convection-based ventilation system that pulls cool air through soffit vents into an airspace and exhausts warm air (heated by the sun) through a vented ridge at the roof. The system creates a constant airflow while the R5 rated foil-backed polystyrene both insulates the attic from conducting heat and reflects over 90% of the sun's radiant heat. This, in turn, reduces cooling costs.

ORNL tested ThermaDeck®'s energy efficiency and benefits and found that it reduces radiant, convection, and conduction heat within an attic by more than 85% compared to conventional composition roofs. Shingle temperatures consistently stayed 10°F cooler than conventional nailed shingle roofs, and the attic air temperature was never more than 5°F warmer than the outdoor air temperature. Attic temperature reduction places less stress on AC systems, reducing HVAC energy expenditures.

Technology History:

The ThermaDeck® roofing system was developed and patented (U.S. Patent No. 7,818,922) by Billy Ellis Roofing LLC and tested by ORNL with support from the BTO. Since it became commercially available in 2012, over 2,500 roofing systems have been installed on homes across the United States.

Applications:

- Can be used in residential applications to reduce heat gain in attics and subsequent heat transfer from an attic to conditioned spaces

Capabilities:

- Reduces peak daytime heat transfer through roofs by 85% compared with conventional roofing
- Maintains attic air temperatures at about the outdoor air temperature

Benefits:

- Reduces cooling costs by minimizing heat transfer from the attic into air-conditioned spaces
- Reduces operational costs by minimizing strain on AC units
- Lasts the lifetime of a home without any need for maintenance or replacement

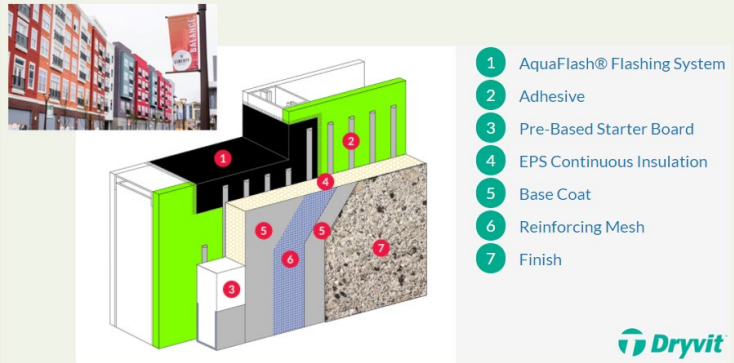
Learn More:

- ThermaDeck ORNL Test Results
- Technology Explanation Video

Contact

Billy Ellis Roofing, LLC
2820 S.E. Loop 820
Worth, TX 76140
www.billyellisroofing.com

B.11 Dryvit® Outsulation®: Energy-Efficient EIFS Wall Systems



Dryvit® Outsulation® construction and building installation (inset)

The insulating performance of a building's envelope plays a major role in determining the building's overall energy efficiency. Exterior insulation and finish systems (EIFS) can be used to increase the insulating value of a building's exterior walls, but are faced with barriers that prevent their widespread adoption (particularly in retrofit applications). Current retrofit solutions for improving envelope energy efficiency require the use of multiple components, such as expanded polystyrene (EPS) insulation and siding. To achieve an R-30 wall, a minimum of eight inches of EPS foam would be required. While this approach is technically feasible, it has poor aesthetics and typically requires the extension of roof flashings and overhangs (resulting in high labor and materials costs). A need exists for exterior insulation products that provide high R-values while minimizing additional wall thickness.

With funding from BTO (as part of the American Recovery and Reinvestment Act), Dow Corning Corporation and Dryvit Systems Inc. integrated vacuum-insulated panels (VIPs) with EPS foam into an improved EIFS design that increases the R-value of a typical wall to R-30 and greater and is only three inches thick. This new technology offers an improved R-value per inch of insulation compared with current envelope systems. The VIP EIFS is adhesively attached to the building's outer walls and can be installed using existing application and finishing techniques. The design lends itself to fabrication in a shop for unitized or modular building construction. Field contractors will be able to easily follow the project application guide to install the system without the need to perform any on-site modifications. The thin cross-section of the VIP EIFS has a minimal impact on wall thickness/living space. The system has been validated for thermal performance and tested to meet industry standards for air/water infiltration, durability, structural performance, flammability, and ease of construction.

Technology History:

Dryvit introduced Outsulation in 1969, and it has been used in over half a million projects worldwide. There have been many product improvements and additional features added in keeping with changing building specification demands, safety, and other design standards and codes, e.g., ASHRAE. The VIP EIFs technology joined Dryvit's line of Outsulation products, which currently includes twelve product variants and multiple combinations of color, finish, veneer, pattern, and textures.

Applications:

- Can be used on residential, commercial, and industrial buildings as new or retrofit construction

Capabilities:

- High R-value with continuous insulation up to four inches thick
- Offers a wide variety of durable, seamless veneers, colors, and finishes to provide an aesthetically appealing look for building owners and homeowners
- Engineered moisture drainage for incidental moisture
- Air and water resistive barrier membrane
- Anti-crack, impact resistant scrim
- Outsulation's elasticity is compatible with rigid surfaces and is hydrophobic, fire, mildew, and fade-resistant

Benefits:

- Provides energy-efficient, cost-effective construction and low maintenance
- LEED Gold Certified
- Improves energy savings by over 30% when compared to modeled performance of identical structures; in field case studies, higher energy cost reductions have been observed

Learn More:

- BTO Final Report
- Product Page

Contact

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