# Building Energy Efficiency Consortium Project Fact Sheets

## DECEMBER 2015

## U.S.-China Clean Energy Research Center

### BEE Projects

# Human Behavior, Standards and Tools to Improve Building Design and Operations

***Joint Project***

## U.S. Partners

- Lawrence Berkeley National Laboratory
- Oak Ridge National Laboratory
- Bentley Systems
- C3 Energy

## China Partners

- Tsinghua University
- Swire Properties
- Yanke Group
- Center for Energy Efficiency in Buildings, MoHURD

## Overview

From real zero-energy buildings in human history, e.g., igloos and pyramids, to the modern, sophisticated multi-service building complex pursuing zero-net-energy (Figure 1), there is a growing challenge to find the optimal solutions integrating technological and human dimensions.

**Figure 1: Evolution of the built environment: from zero-energy to the zero-net-energy challenge**

To achieve low- or zero-net-energy buildings, energy efficiency technologies, integrated building design and operation, regulations for building and appliance codes and standards, and support from other energy policies are necessary (Figure 2). There are six driving factors that determine the energy performance of buildings: climate, building envelope, building equipment (energy service systems including HVAC, lighting and plug loads), operation and maintenance, occupant behavior, and indoor environmental conditions. Understanding how these factors affect the energy performance of buildings and which factors play more significant roles under certain conditions can provide insight into the large variations of building energy use and strategies to improve the design and operation of buildings for lower energy use and lower carbon emissions.

Figure 2: Key drivers of low-energy buildings

This five-year research project included four sub-projects: (1) the building energy monitoring and analysis project (2011–2013) reviewed building energy monitoring and management systems in the United States and China, and compared actual energy use in typical office buildings in both countries to understand their similarities and differences in energy efficiency technologies, design and operation strategies, and occupant behavior in buildings; (2) the building performance simulation project (2011–2013) developed methods and simulation models to quantify impacts of multi-year weather variation, HVAC operational faults, and occupant behavior on building energy use; (3) the building codes and standards project (2013–2014) developed an ontology to represent energy use in buildings (a key component of ISO Standard 12655), and analyzed the China design standard for energy efficiency of public buildings GB 50189-2015, as well as the China standard for energy consumption of buildings; and (4) the occupant behavior research project (2013–2016) developed new data, methods, tools, and case studies to improve occupant behavior modeling in building performance simulation.

The project is successfully completed with significant outcomes that can be used to improve building design and operations for low-energy buildings in the United States and China. The intellectual gains from the project enable the LBNL and Tsinghua team to establish and lead two large research efforts on occupant behavior in buildings: (1) Annex 66: Definition and simulation of occupant behavior in buildings, under the International Energy Agency's Energy in Buildings and Communities (IEA EBC) Programme; and (2) the ASHRAE Multidisciplinary Task Group on occupant behavior in buildings (MTG.OBB). The outcomes from the occupant behavior research will be further integrated and applied to the CERC-BEE 2.0 (2016–2021) occupancy responsive model-predicted control project.

## Research Objectives

The primary goal of this project is to gain a deep understanding of key factors influencing energy use in buildings in the United States and China. The research objectives are to develop and apply (1) methods for building energy data definition, collection, presentation, and analysis; (2) methods and models to identify and evaluate key factors influencing building energy performance; (3) models and tools to describe and model occupant behavior in buildings, and integrate the behavior models with EnergyPlus and DeST (two popular and most powerful building simulation programs used in the U.S. and China) to simulate and quantify the impact of occupant behavior on building performance, thus to improve building design and operations for better energy efficiency and energy savings.

Technologies alone do not guarantee low energy use in buildings; human behavior also plays an essential role in building design and operation. However, case studies and data are needed to understand human behavior's role in energy efficiency. This project aims to create that data, to standardize the description of human energy-related behavior, and then to integrate those behavior models into whole-building performance simulation tools. This project makes significant technical contributions to the international project IEA EBC Annex 66.

The research outputs from the project helped better understand energy performance of buildings, improve building operations, and provide guidelines to improve the design of energy-efficient buildings by integrating human behavior insights. Moreover, the project aims to improve and expand the use of building simulation through better understanding and predicting the energy performance of buildings.

The research team estimated that understanding, and subsequently correcting, overcoming, or optimizing occupant behavior—or alternatively designing buildings and operation schemes that better align with occupant behavior—can reduce building energy use by 5% to 50%. The developed behavior tools can be used by energy modelers, building designers, engineers, operators, and policymakers. The IEA EBC Annex 66 project and the ASHRAE MTG.OBB will further advance human behavior research and applications to support the energy goals of the DOE Building Technologies Office.

## Major Accomplishments

The project developed new data, methods, tools, and case studies to gain a deep understanding of energy use in buildings and the driving factors, and integrate human behavior insights, through data analytics, modeling and simulation, in building design and operations to reduce energy use and GHG emissions. Three occupant behavior modeling tools were developed and released: (1) the Occupancy Simulator to simulate occupant presence and movement in buildings and generate occupant schedules for building performance simulation, (2) obXML, an ontology and XML schema to standardize representation and exchange of occupant behavior models for building performance simulation, and (3) obFMU, a functional mockup unit of occupant behavior models for co-simulation. Thirty peer-reviewed journal articles were published. The project established intellectual leadership in occupant behavior research, which enables the LBNL and Tsinghua University to jointly establish and lead the international collaboration project IEA EBC Annex 66 with more than 100 researchers from 20 countries. The joint U.S.-China research team also formed and leads the new ASHRAE MTG.OBB. The project also made significant contributions to the ISO Standard 12655 and the China building energy design standard GB 50189-2015 and the new building energy consumption standard.

## Summary of Research Activities

### Years 2011-2013: Building Energy Monitoring and Analysis

**OBJECTIVES**

- Establish a standard methodology for building energy data definition and presentation
- Collect and analyze building energy use data to compare office buildings in both countries

**SUMMARY OF TASKS**

- Compared existing building energy monitoring systems, including iSagy, Pulse Energy, SkySpark, sMap, EPP, ION, and Metasys
- Developed a standard data model to describe energy use in buildings
- Developed three-level data analysis methods: energy profiling, benchmarking, and diagnostics
- Selected a few buildings in the U.S. and China to collect three types of data: energy use, system and equipment operating conditions, and indoor and outdoor environmental conditions
- Analyzed the collected building data to quantify building performance, understand the drivers to discrepancies, and identify potential energy-savings measures

**MAJOR FINDINGS AND OUTCOMES**

- There is a strong need for a standard data model and platform to collect, process, analyze, and exchange building performance data.
- Existing energy monitoring systems have diverse features and uses; all had challenges of data interoperability.
- A standard data model to represent energy use in buildings (ISO Standard 12655) was developed and applied to Chinese national standard (Figure 3).
- Determination and highlighting of diverse buildings design, operation, maintenance, and

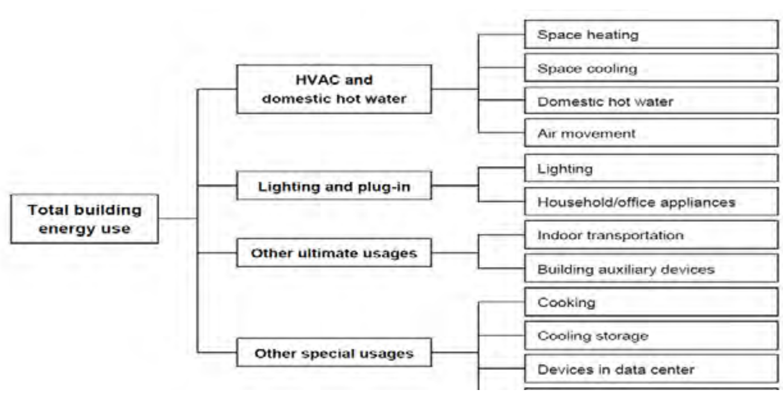


Figure 3: ISO Standard 12655 – Energy Use Data Model

occupant behavior in the United States and China. U.S. buildings have more stringent comfort standards regarding temperature, ventilation, lighting, and hot water use and, therefore, higher internal loads and operating hours. Chinese buildings having higher lighting energy use; seasonal heating, ventilation, and air conditioning (HVAC) operation; more operators; more use of natural ventilation; less outdoor ventilation air; and a wider range of comfort temperature (Figure 4).

- Completed data collection for four office buildings: one on the University of California, Merced campus; one in Sacramento; and two in Beijing.
- Development and application of methods in data analysis of building performance for the four buildings with adequate data, including energy benchmarking, profiling, and diagnostics.

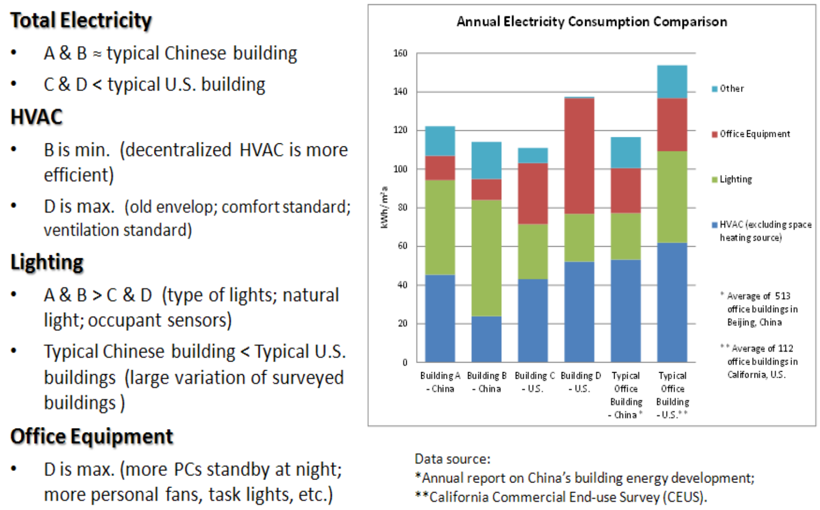


**Figure 4: Benchmarking energy performance of case study buildings**

- Recommendations for energy efficiency measures for building retrofit in both the United States and China. U.S. buildings show more potential savings by reducing operation time, reducing plug loads, expanding comfort temperature range, and turning off lights or equipment when not in use; while Chinese buildings can save energy by increasing lighting system efficiency and improving envelope insulation and HVAC equipment efficiency.

## Years 2011-2013: Building Performance Simulation

### OBJECTIVES

- Use and improve building simulation to better understand building energy use data in China and the U.S.
- Understand and identify key driving forces behind the energy performance of buildings by developing new methods to describe and model these factors
- Evaluate and compare the capabilities of DOE-2.1E, Designer's Simulation Toolkit (DeST), and EnergyPlus to better understand their strengths and weaknesses, which will support their use for energy code development and code compliance in China

### SUMMARY OF TASKS

- Performed sensitivity and scenario analysis to quantify the relative impact of the six driving factors of the energy performance of buildings
- Identified the key energy-related practices of operation and maintenance, and evaluated their impact on building performance
- Developed methods to describe occupant behavior in buildings based on measured and survey data
- Developed algorithms to model occupant behavior and evaluated its impact on building energy use
- Compared DOE-2.1E, DeST, and EnergyPlus to evaluate their capabilities and limitations and recommend their use in energy modeling.
- Four workshops and seminars on occupant behavior simulation and case studies were conducted in Hong Kong, Shanghai, Xi'an, and Berkeley

### MAJOR FINDINGS AND OUTCOMES

- Completed a series of sensitivity and scenario analysis of weather, building operation and maintenance, and occupant behavior. These factors have significant influences on building energy use and must be considered in evaluating energy efficiency measures during building design and operation.
- New methods and test cases were developed to compare building energy simulation programs.
- New mathematical models were developed to represent occupant behavior of presence, use of air-conditioning and lighting in buildings

## Year 2013-2014: Building Energy Codes and Standards

**OBJECTIVES**

- Provide technical support to develop and evaluate three building energy standards in China: the Standard for Energy Consumption of Buildings, the Design Standard for Energy Efficiency of Public Buildings (GB 50189-2015), and the Design Standard for Very Low Energy Buildings

**SUMMARY OF TASKS**

- Developed a technical framework and approach to the development of China Design Standard for Very Low Energy Buildings
- Reviewed the definition of "very low energy buildings" and some technical pathways for the realization of "very low" energy consumption, from standards, regulations, and research on high-performance buildings and nearly zero energy buildings in the U.S. and Europe (ASHRAE standard 189.1, EU EBPD)
- Evaluated China Standard for Energy Consumption of Buildings and discussed the under-development U.S. outcome-based building energy codes
- Compared China Design Standard for Energy Efficiency of Public Buildings against ASHRAE Standard 90.1
- An integrated design workshop was conducted in Wuhan, China during the annual CERC-BEE technical review

**MAJOR FINDINGS AND OUTCOMES**

- A technical framework was developed for China Design Standard for Very Low Energy Buildings
- Recommendations were provided to guide the future standard revision of GB 50189, focusing on three areas: (1) increasing efficiency requirements of building envelope and HVAC systems, (2) adding a whole-building performance compliance pathway and implementing a ruleset-based automatic code baseline model generation in an effort to reduce the discrepancies between baseline models created by different tools and users, and (3) adding inspection and commissioning requirements to ensure building equipment and systems are installed correctly and operate as designed
- Analysis of China Standard of Energy Consumption of Buildings and comparison with U.S. outcome-based codes

## Years 2013-2016: Modeling and Simulation of Occupant Behavior in Buildings

**OBJECTIVES**

- Develop a systematic approach to study the human energy behavior loop in buildings, gaining a deep understanding of energy-related occupant behavior in buildings. As shown in Figure 5, the three steps of the technical approach to the human energy behavior loop are: (1) Investigate building operations through behavioral data collection, (2) Understand the human behavior through standardized representation, data analytics and modeling, and (3) Improve the building performance by applying behavioral solutions.
- Use data mining methods and tools to analyze patterns of occupant behavior from human-building interaction datasets for office and residential buildings

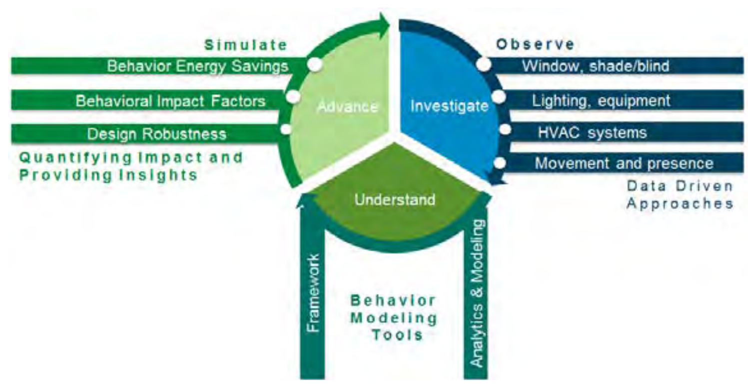


Figure 5: The Human Energy Behavior Loop in Buildings

- Develop and release occupant behavior modeling tools to improve occupant-related input and assumptions in energy models
- Provide technical leadership for the IEA EBC Annex 66

**SUMMARY OF TASKS**

- Developed a standardized description of human energy-related behavior.
- Developed a software module of occupant behavior models.
- Developed a web application to simulate occupant movement in buildings to generate occupant schedules for building performance simulation.
- Integrated and tested the occupant behavior modeling tools with EnergyPlus.

- Introduced the three occupant behavior modeling tools in a webinar with 100 participants from academia, research and industry.
- Continued to manage IEA EBC Annex 66 and lead Subtask D: Development and integration of occupant behavior models with building performance simulation programs

**MAJOR FINDINGS AND OUTCOMES**

- Development of an analytic framework combining statistical analysis with data-mining techniques and applied them on a data repository, to reveal the operational patterns of occupant behavior in office buildings (window opening, occupancy) and residential buildings (indoor temperature, and space heating).
- Creation and integration of three behavior modeling tools with EnergyPlus.

The Occupancy Simulator is a web App for simulating occupant presence and movement in buildings. The App takes high-level input on occupants, spaces, and events, then simulates occupant movement using a Markov-chain model. The simulator generates occupant schedules for each space, which captures the diversity and stochastic nature of occupant activities (Figure 6).


**Figure 6: Schedules of occupancy generated by the Occupancy Simulator (occupancysimulator.lbl.gov)**

The obXML (occupant behavior eXtensible Markup Language) is a standardized semantic information model for the representation of occupant behavior models that enable interoperability. The obXML schema is built upon an ontology of energy-related behavior in buildings integrally embedded into a DNAS (Drivers, Needs, Actions, Systems) framework (Figure 7).

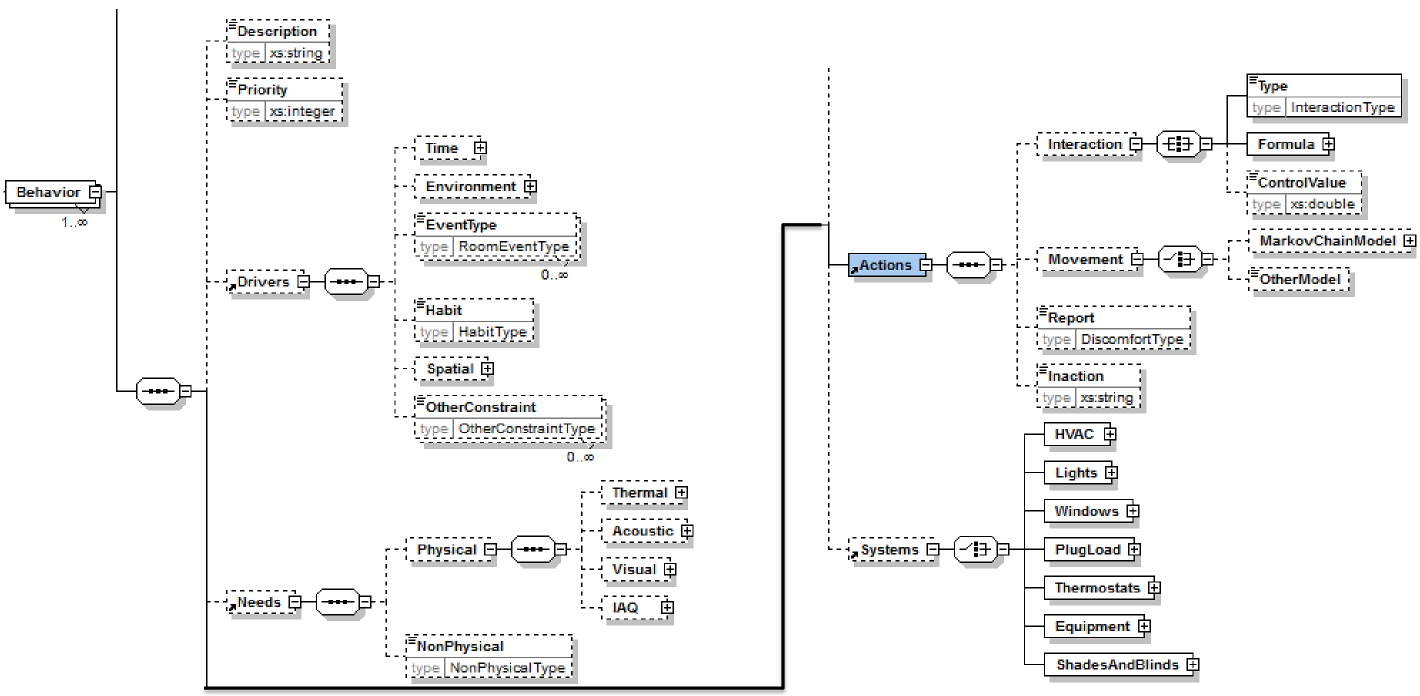


**Figure 7: Structure of the obXML syntax, grounded on the DNAS ontology for energy-related behavior in buildings**

The obFMU, a functional mockup unit (FMU) of occupant behavior models for co-simulation with building simulation programs like EnergyPlus. The tool can implement occupant behavior models for system controls (i.e., on, off, proportional control) of various windows, shades/blinds, lights, plug loads, thermostats, and HVAC, and it allows the simulation, numerous probabilistic models, occurring at different events (Figure 8).

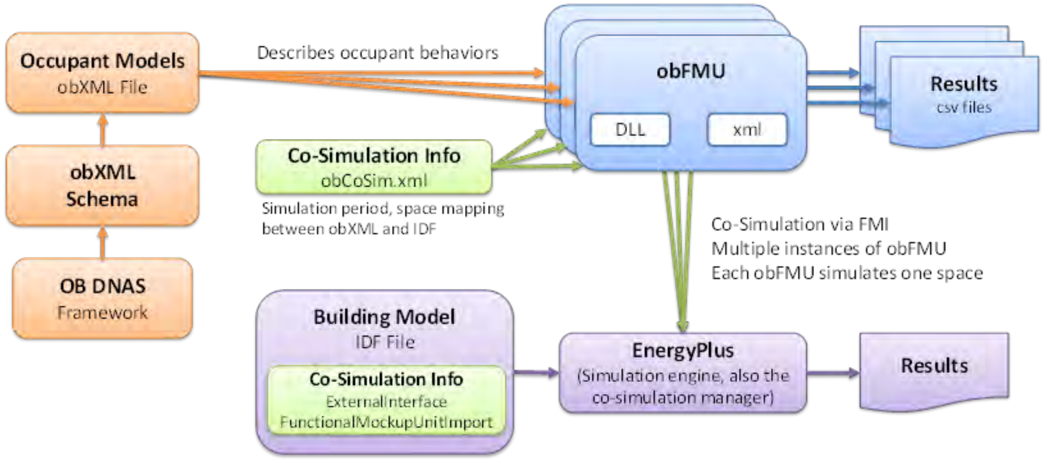


Figure 8: System Architecture of the obFMU, connection with the obXML Schema and co-simulation with EnergyPlus

- Annex 66 leveraged international effort from 20 countries to conduct research on occupant behavior sensing, data collection, analytics, modeling and simulation, as well as case studies to demonstrate occupant behavior impact on building design and operations.
- Formed the new ASHRAE Multidisciplinary Task Group on occupant behavior to promote research and integrate behavioral insights into ASHRAE handbooks, guidelines, codes and standards.
- Seven workshops, seminars and webinars were conducted to disseminate the knowledge gains.
- Publication of 20 peer-reviewed journal articles on occupant behavior in buildings.

## Major Outcomes and Achievements

### Products Launched

Three occupant behavior modeling tools are developed and made available for public use at behavior.lbl.gov and occupancysimulator.lbl.gov.

- The Occupancy Simulator, a web App for simulating occupant presence and movement in buildings.
- The obXML, an XML schema for representation and exchange of occupant behavior models.
- The obFMU, a functional mock-up unit (FMU) of occupant behavior models for co-simulation with building performance simulation programs such as EnergyPlus and ESP-r.

### Standards, Codes, and Policies influenced

- Creation and chairing the ASHRAE Multidisciplinary Task Group on occupant behavior in buildings to promote occupant behavior research and integrate the behavior insights into ASHRAE handbooks, guidelines, codes and standards
- Significant contribution to the development of:
    - ISO Standard 12655-2013, Energy performance of buildings: Presentation of measured energy use of buildings.
    - China Design Standard for Energy Efficiency in Public Buildings, GB 50189-2015.
    - China Standard for Energy Consumption of Buildings, a national standard (GB # tba), 2015.

### Workshops

- Webinar on occupant behavior modeling tools, March 15, 2016. LBNL.
- Workshop on occupant behavior in buildings, during the ISHVAC-COBEE conference, July 12 to 15, 2015. Tianjin, China.
- ASHRAE seminar on occupant behavior in buildings, Annual Meeting. June 2015. Atlanta.
- International Technical Forum on occupant behavior in buildings, March 30, 2015. LBNL.
- ASHRAE seminar on occupant behavior in buildings, Winter Meeting. January 2015. Chicago.
- Seminar on occupant behavior research at LBNL, October 6, 2014. IBPSA-USA San Francisco Chapter. Oakland.
- Second Workshop on Human Energy-Related Behavior in Buildings, August 28, 2014, LBNL.
- ASHRAE seminar on occupant behavior in buildings, Annual Meeting, June 2014. Seattle.
- Workshop on occupant behavior in buildings, during the 8th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC), October 18 to 20, 2013. Xi'an, China.

- First Forum on Human Behavior and Integrated Design for High Performance Buildings, July 17-18, 2013. LBNL.
- Human Behavior Simulation Workshop, July 16, 2012. Hong Kong, China.
- Human Behavior Simulation Workshop, November 26, 2012. Shanghai, China.

## List of Publications

Scientific publication of 30 peer-review journal articles and a dozen seminars, workshops and webinars to disseminate the knowledge gains. A total of 30 journal articles, 11 conference papers, and 5 technical reports were published.


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## Collaboration

The CERC-BEE project was partnered with Bentley Systems which provided guidance on the project plan, participated in meetings and conference calls, reviewed and tested the occupant behavior modeling tools. The outcomes from the CERC 1.0 project will be deployed and further refined at the CERC 2.0 occupancy responsive model predictive controls project, with more industry partners, including JCI, UTC, Disney, Lutron and Lend Lease.

The U.S. research team closely collaborated with the research team at Tsinghua University. The team worked jointly on technical tasks, organizing workshops and seminars, and publications. A total of ten faculty and students visited and participated in joint research tasks at LBNL. The LBNL and Tsinghua teams jointly established IEA EBC Annex 66 and ASHRAE MTG.OBB. The LBNL and Tsinghua collaboration will continue in the CERC 2.0 project, IEA EBC Annex 66, and ASHRAE MTG.OBB.

## Conclusions

Human dimension, with seamless integration of technologies, is critical to achieving low- or zero-net- energy buildings in the U.S. and China. The CERC-BEE 1.0 project successfully achieved the envisioned goals, providing both the research and industry sectors with tangible outcomes. These include extensive publications in peer-reviewed journals; project results outreach by workshops and seminars as well as the development of international and China building energy standards and modeling tools of energy-related occupant behavior in buildings. The outcomes and partnership from CERC 1.0 establish a strong foundation for the CERC 2.0 project, which we expect to develop further and apply human behavior tools and insights to building control systems to improve building operations to reduce energy use and GHG emissions. The joint U.S.-China project team will continue to lead the IEA EBC Annex 66 and ASHRAE MTG.OBB, and to promote occupant behavior research and application to broader academic, research, and industry sectors.

# Advanced Window and Shading Technologies

***Joint Project***

## U.S. Partners

- Lawrence Berkeley National Laboratory
- Saint-Gobain
- Sage Electrochromics
- 3M
- Lutron Electronics Co., Inc
- Dow Chemical Company

## China Partners

- Tongi University
- Chongqing University
- Saint-Gobain Research (Shanghai) Co. Ltd

## Overview

This report summarizes the various research activities conducted under the CERC-BEE 1.0 program to develop, evaluate, and promote advanced energy-efficient window and shading technologies in the U.S. and China in order to achieve significant energy savings and reduced greenhouse gas emissions in both countries. The R&D activities were conducted in close collaboration with industry partners in the U.S. and with industry and academic partners in China. Research activities over the five- year term of the project include assessments of the technical and market potential of advanced technologies, use of state-of-the-art simulation tools toward the development and application of new technologies in buildings, development and testing of integrated demand/supply side control systems in order to achieve ambitious zero net energy goals, full-scale field testing of emerging dynamic façade systems, monitored demonstrations, and occupant/ human factors studies. These activities enabled researchers and manufacturers to demonstrate and evaluate the complex value proposition of innovative fenestration solutions within a broader international context and engage with government organizations and leading-edge developers of commercial properties in China.

## Research Objectives

- To support further development of advanced fenestration technologies by industry so as to improve cost-effectiveness, user comfort, and market applicability in the U.S. and China
- To evaluate whether innovative solar control and daylighting technologies provide 40-50% perimeter zone energy savings compared to China's GB 50189-2005 while meeting comfort constraints in real world building applications
- To accelerate market adoption of advanced fenestration technologies in the U.S. and China markets by demonstrating successful use in real building projects

## Major Accomplishments

- Demonstration of advanced switchable electrochromic windows, dimmable lighting, and low-energy cooling strategies were shown to result in cost-effective net-zero building energy performance when integrated with building integrated PV (BIPV)
- Implementation of a Model Predictive Control (MPC) framework which includes disturbance estimation, glare model, state estimation, and optimization. Application of the MPC framework for zone-level MPC in simulation was shown to result in energy savings when compared to a baseline

## Summary of Research Activities

### Year 2011

**OBJECTIVES**

- Encourage adoption of standard calculation procedures for evaluating glazing and optically-complex fenestration systems so that products can be compared. Encourage adoption of the calculation methods by the building industry and energy-efficiency codes and standards

- Identify and evaluate the technical and market potential of advanced, innovative fenestration technologies and determine whether they meet the very low energy goal of 40-50% savings compared to the GB 50189-2005 Standard in collaboration with U.S. and Chinese partners

**SUMMARY OF TASKS**

- Standardized measurement and calculation procedures
- Since the early 1990s, glass manufacturers from around the world have measured their products using protocols defined by international standards and submitted these data to the International Glazing Database (IGDB). The Ministry of Housing and Urban Development (MOHURD) and industry organizations initiated discussions with LBNL in early 2010 on how to measure window properties to enable entry of Chinese products to the IGDB, with a first training session occurring in August 2010 at LBNL
- In October 2010, MOHURD agreed to begin to adopt the International Standards Organization ISO 15099, which specifies the detailed calculations procedures for determining the thermal and optical transmission properties of window systems. Data submissions were first received in November 2010 and a second international training workshop was held at LBNL in February 2011.Manufacturers were then qualified to submit data after successfully participating in an inter-laboratory comparison
- A workshop was conducted to introduce the methods and measurement tools needed to model complex fenestration systems (CFS) to MOHURD in February 2011. The goniophotometer used to measure Bidirectional Scatter Distribution Function (BSDF) data was demonstrated. In parallel, collaborative work occurred with the U.S. industry to work out how the CFS methods could be adopted into rating and labeling programs for common shading systems (roller shades, venetian blinds, cellular shades, etc.)
- Technical potential of innovative technologies
- A simulation study was conducted to investigate the energy savings potential of several alternate fenestration systems and gauge their performance relative to China's GB 50189-2005 Standard
- Parametric analysis of a various window and shade combinations using EnergyPlus indicated that for both the cold Beijing climate, and hot summer and cold winter Shanghai climate, the spectrally-selective low-e dual pane window with an exterior roller shade and the triple pane window with an exterior roller shade provided the best performance in terms of energy savings, while the spectrally-selective low-e dual pane window with an exterior roller shade was more economically attractive due to its lower cost
- The economics of such solutions was highly dependent on the specifics of the space conditioning. If occupants were not using space conditioning either due to thermal preferences defined by adaptation to a broader range of environmental conditions or for reasons of economy given that energy costs are high, then the economics of the solution must be judged based on how the solution improves thermal comfort and habitability of indoor spaces

**MAJOR FINDINGS AND OUTCOMES**

- Standardized measurement and calculation procedures
- All ten Chinese manufacturers are now contributing measured spectral, conductance, and emittance data for their glazing products to the IGDB, coordinated through the China National Safety Glass and Quartz Glass Test Center
- A Chinese version of LBNL's WINDOW software was rewritten in collaboration with LBNL and is now being distributed by the Guangdong Provincial Academy of Building Research (PABR)
- Technical potential of innovative technologies
- Researchers from the U.S. (LBNL, Saint-Gobain, & Dow Chemical) and China (Chongqing & Tongji Universities) completed a technical assessment of the energy savings potential of energy-efficiency measures that are likely to produce significant reductions in energy use in commercial buildings and published the findings in a journal article. Compared to the energy-efficiency code in effect in China, conventional low-emittance windows with exterior operable shading are able to achieve up to 66% savings in perimeter zone HVAC electricity consumption, 5% savings in district heating energy in the cold climate of Beijing, and up to 42% savings in HVAC electricity consumption in the hot/cold climate of Shanghai. Highly insulating windows also had a significant effect on reducing energy use. Shading attachments are likely to be a near-term, low-cost solution for retrofit and new construction in both the United States and China

## Year 2012

### OBJECTIVES

- To the extent possible, develop demonstration opportunities for emerging fenestration technologies in U.S. and China to evaluate constructability, economic feasibility, energy performance, and indoor comfort and environmental quality
- Use these demonstration opportunities to prove that the technology delivers on performance claims within the unique Chinese building context to increase confidence in emerging technologies and accelerate adoption

### SUMMARY OF TASKS

- Exterior shading for a Class A commercial office building development
- A Chinese developer invited LBNL to collaborate on a 600,000 ft2 mixed use knowledge community project with the goal of achieving aggressive net zero energy use in this and future buildings and to establish a new process by which the results from the collaboration could be repeated in the future. The developer had built extensively throughout China, owned an estimated 1+ million square meters of floor area, and had plans to build many more buildings over the ensuing decade. Lessons learned could potentially be extended to 15 Mm2 of similar new communities throughout China, potentially affecting 50,000-300,000 building occupants
- The LBNL team engaged with the design team to review design options and technical approach. In support of decision making, an energy analysis was conducted of exterior shading options using the LBNL COMFEN tool. Recommendations were made as to the optimum depth of overhangs and types of glazing that could be used with the exterior shading to minimize lighting and HVAC energy use
- A monitored field study in a full-scale mockup was planned but the aggressive schedule for final specifications, bid, and construction did not complement the field test schedule
- Electrochromic (EC) windows demonstration in the Saint-Gobain Research Shanghai headquarters
- The Saint-Gobain Research (Shanghai) (SGRS) center was building a new three-story 8351 m2 building adjacent to their existing R&D center in the next few years. The objective of the center was to develop innovative products and support local businesses in the Asian market. SGRS expressed interested in collaborating with LBNL to support a monitored EC window demonstration in their new building
- LBNL held a series of discussions with SGRS and Sage Electrochromics to define and work out the research objectives, technical approach, construction of the test rooms, instrumentation, and monitoring details. LBNL continued to provide technical support as the three-story research center was under construction

### MAJOR FINDINGS AND OUTCOMES

- Initiated the development of a monitored testbed in collaboration with Saint Gobain to demonstrate electrochromic windows in a Shanghai office building


**Figure 1: Architectural rendering of a 600,000 ft2 mixed use knowledge community (office + retail). Credit: Gensler.**

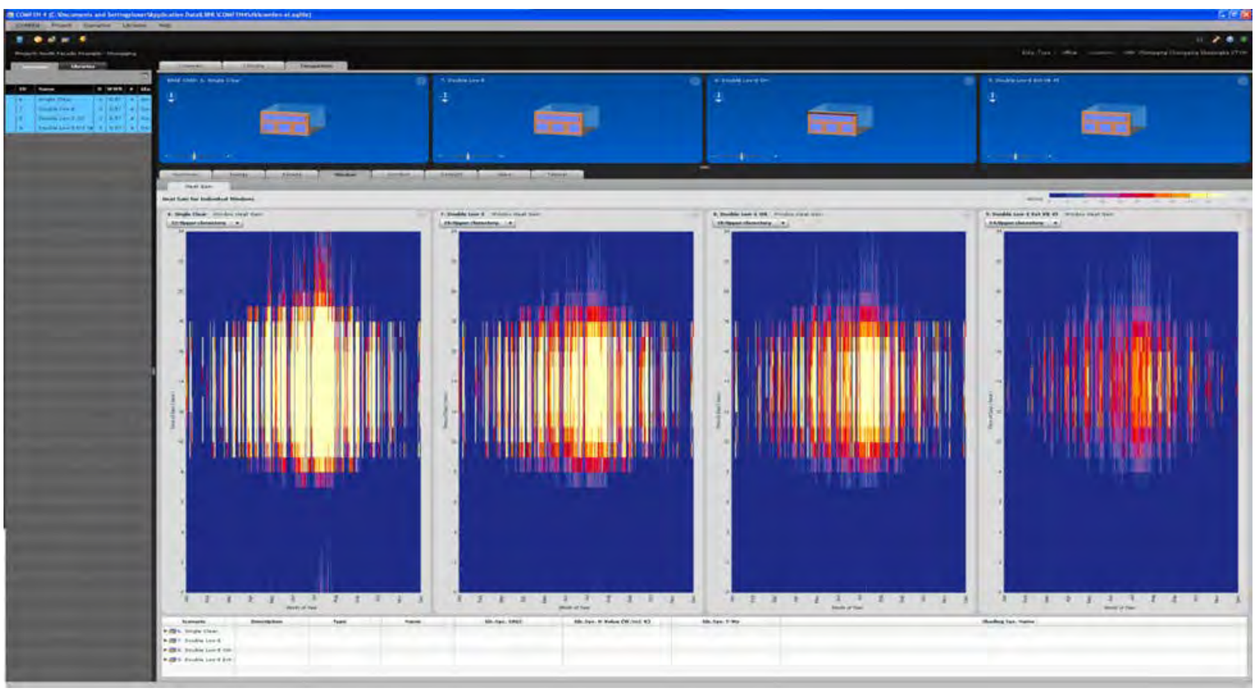


**Figure 2: Example output from the COMFEN tool. This image depicts temporal window heat gains as a function of time of day and day of year for the Chongqing climate.**

Figure 3: Interior of the existing Saint-Gobain Research (Shanghai) (SGRS) center.

Figure 4: Rendering of the new addition to the Saint-Gobain Research Center in Shanghai where electrochromic windows will be evaluated in two side-by-side conference rooms.

## Year 2013

**OBJECTIVES**

- Develop demonstration opportunities for emerging fenestration technologies in US and China to evaluate constructability, economic feasibility, energy performance, and indoor comfort and environmental quality
- Support industry partners in the development and evaluation of incremental improvements to emerging dynamic fenestration products via laboratory and physical testing in the LBNL Advanced Windows Testbed and demonstrations in China

**SUMMARY OF TASKS**

- Demonstrations
- SGRS EC Demonstration: Initiated baseline metering at the SGRS demonstration site in late 2013. EC and reference windows were to be installed in two side by side conference rooms so occupancy occurred on an intermittent basis. A monitoring protocol was developed to study occupant comfort and satisfaction while performing office tasks in the conference room during scheduled periods of evaluation
- Zhuhai Singye Green Building Technology Building Demonstration: Worked with the developer to define the project scope for a potential demonstration of Sage EC windows and/or Lutron automated shading and advanced lighting controls in a new commercial office building in Xingye, China
- CABR Demonstration: Worked with CABR researchers to define the project scope for a potential demonstration of Sage EC windows and/or 3M's daylight redirecting film in a new commercial office building in Beijing, China
- Technology R&D
- Sage EC field test: Conducted a six-month field test of the Sage EC window system in the LBNL Advanced Windows Testbed in parallel with the SGRS demonstration in order to more thoroughly evaluate the daylighting/ visual comfort performance of the Sage control system
- Lutron field test: Developed workplan, defined hardware and controls specifications, then field tested Lutron's automated roller shades in the LBNL Advanced Windows Testbed. The main test objective was to develop a better understanding of the performance of Lutron's state of the art glare and daylighting control algorithms using several combinations of sensors and shade fabrics
- Dow Chemical: Demonstrated use of complex fenestration system (CFS) simulation tools by modeling several of Dow's prototype designs and explaining how the tool is used to evaluate illuminance and discomfort glare performance. A one-hour detailed tutorial was developed to explain use of the genBSDF tool (which is used to generate the bidirectional scattering distribution function data for a shading system) and this material was then used in a face-to-face educational session

**MAJOR FINDINGS AND OUTCOMES**

- Demonstrations
- Initiated monitoring in collaboration with Saint Gobain Research Shanghai and Tongji University to evaluate electrochromic windows in a Shanghai office building
- The developer declined potential demonstration of US technologies at the Xingye site due to concerns regarding high initial cost for the technologies
- CABR remained interested in demonstration of EC windows but was unable to accommodate the technology in the first phase of field testing. Applicability of the 3M film was found to be less than optimal due to pre-existing between-pane blinds in the facility
- Technology R&D
- Improved prototype emerging technologies based on quantitative feedback from laboratory and field studies in collaboration with industry
- Supported controls research and development through physical testing of pre-commercial dynamic fenestration systems in the LBNL Advanced Windows Testbed. Evaluated Sage Electrochromics and Lutron open-loop control systems that automatically actuate switchable window coatings or automated roller shades, respectively, in response to incident daylight levels and solar position. Both control systems were found to adequately control discomfort glare due to bright sky conditions over the summer solstice to equinox period; however, daylight illuminance levels were low, resulting in less lighting energy savings than optimal. Field testing enabled industry partners to finetune control

settings in a highly instrumented facility then study the tradeoffs between the two competing performance metrics in preparation for potential application at demonstration sites in China

- Dow Chemical expressed interest in further development of their prototype technology using LBNL tools but continued engagement was curtailed due to commitments on other CERC tasks

**Figure 5: Installation of Sage electrochromic windows (righthand windows in the photo) in the LBNL Advanced Windows Testbed.**

**Figure 6: The performance of low-emittance windows with manually operated roller shades (left) are being compared to automated switchable electrochromic windows (right) in the Saint-Gobain Research Shanghai building. Each of the three rows of electrochromic windows are switched independently according to daylight availability and the position of the sun. The windows can be opened manually for ventilation.**

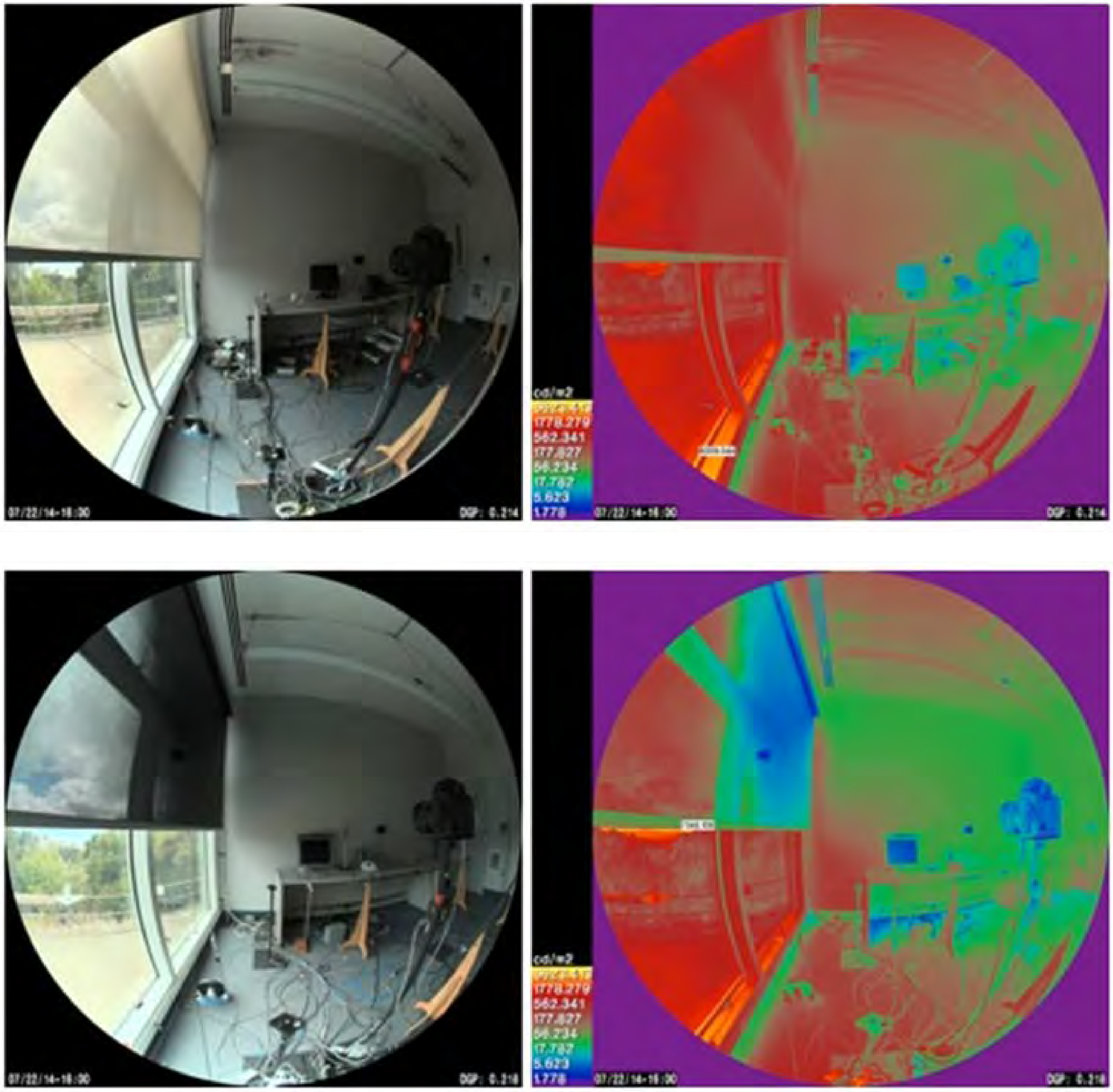


**Figure 7: Comparison of view and illuminance levels (left images) and field-of-view luminance (right falsecolor maps) in two test rooms with a white roller shade (top row) in one room and a black roller shade (bottom row) in the other (July 22, 4 PM). Outdoor views were better and glare was lower with the dark-colored shade but daylight levels were lower compared to an unshaded window. Lutron's control settings could be better tuned to raise the shade to admit daylight within glare constraints.**

## Year 2014

**OBJECTIVES**

- Broaden the value proposition for automated shading and daylighting technologies so that the technologies may be more rapidly and cost effectively deployed in residential and commercial buildings throughout China and the US
- Develop a second-generation control system that provides control of demand-side technologies (e.g., dynamic envelope technologies, daylighting, low energy cooling) and supply side resources (e.g., PV, storage) to minimize energy and demand costs based on forecast data, meet real-time comfort criteria, and flatten fluctuations on the grid
- Reduce perimeter zone annual energy use by an additional 10% above and beyond that achieved by dynamic façade technologies with heuristic controls or 40-50% perimeter zone total energy savings compared to China's GB 50189-2005

**SUMMARY OF TASKS**

- Demonstrations
- SGRS EC Demonstration: Installed EC windows then initiated monitoring in the side-by-side conference rooms. Conducted occupant surveys during solstice and equinox periods
- Technology R&D

- Initiated a field study to determine whether dynamic facade technologies such as EC windows can play an enabling role in supporting a desired level of electricity service at either minimum operating cost or minimum carbon footprint through optimized integrated control with distributed energy resources
- A proof-of-concept control system was developed by approximating non-linearities as piecewise-linear and determining the control state of both the demand and supply side components through global optimization
- Annual simulations of a south-facing office zone with switchable electrochromic windows, solar photovoltaic electricity generation, and battery storage indicated that with optimized integrated demand-supply side controls, the utility grid load profile could be lowered to nearly zero demand (5 W/m2) during the daytime when energy costs were highest
- A full-scale outdoor field test in the Advanced Windows Testbed at LBNL was used to verify actual performance of the prototyped system over a winter period

**MAJOR FINDINGS AND OUTCOMES**

- Demonstrations
- Evaluated energy use and human factor impacts of the Sage switchable electrochromic windows in the new west wing of the Saint-Gobain Research Center in Shanghai. Results from the subjective surveys were consistent with LBNL measured data in the Advanced Windows Testbed: glare was controlled but indoor illuminance levels were found to be low compared to conventional shaded windows when occupants performed office-type tasks (e.g., paper- and computer-based tasks)
- Technology R&D
- Explored the integration of dynamic fenestration technologies within the whole building, microgrid, and grid context to determine if demand-supply side control strategies can improve cost-effectiveness and applicability in US and China markets. Developed software to generate a seven-day-ahead schedule for controlling the dynamic fenestration and distributed energy sources (photovoltaics, electrical storage) to minimize energy cost or carbon emissions. Results from a full-scale field test demonstrated that during a week of sunny winter weather, electricity bills could be reduced by 63% compared to heuristic control of electrochromic windows. Technical and market challenges for achieving reliable optimal control for widespread applications were evaluated

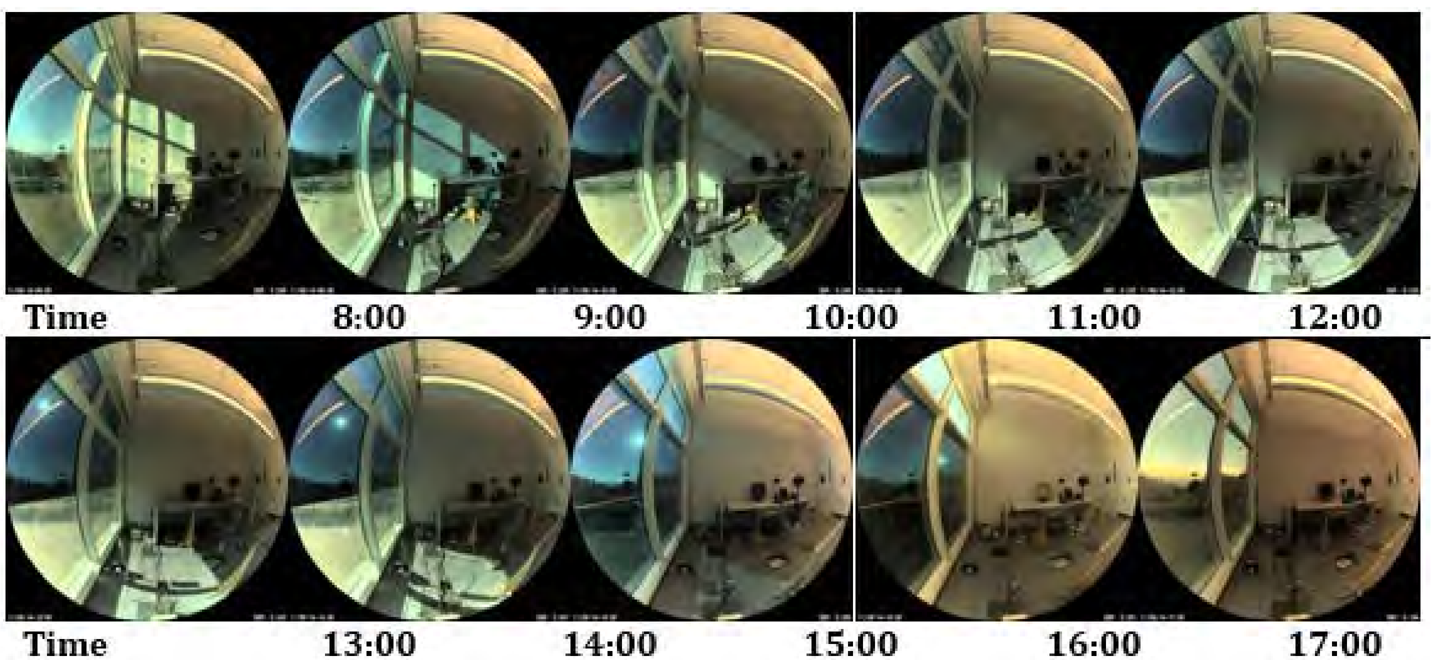



Figure 8: Indoor photographs of the three-zone electrochromic window being switched over the course of a sunny day with heuristic controls on November 9, 2014.

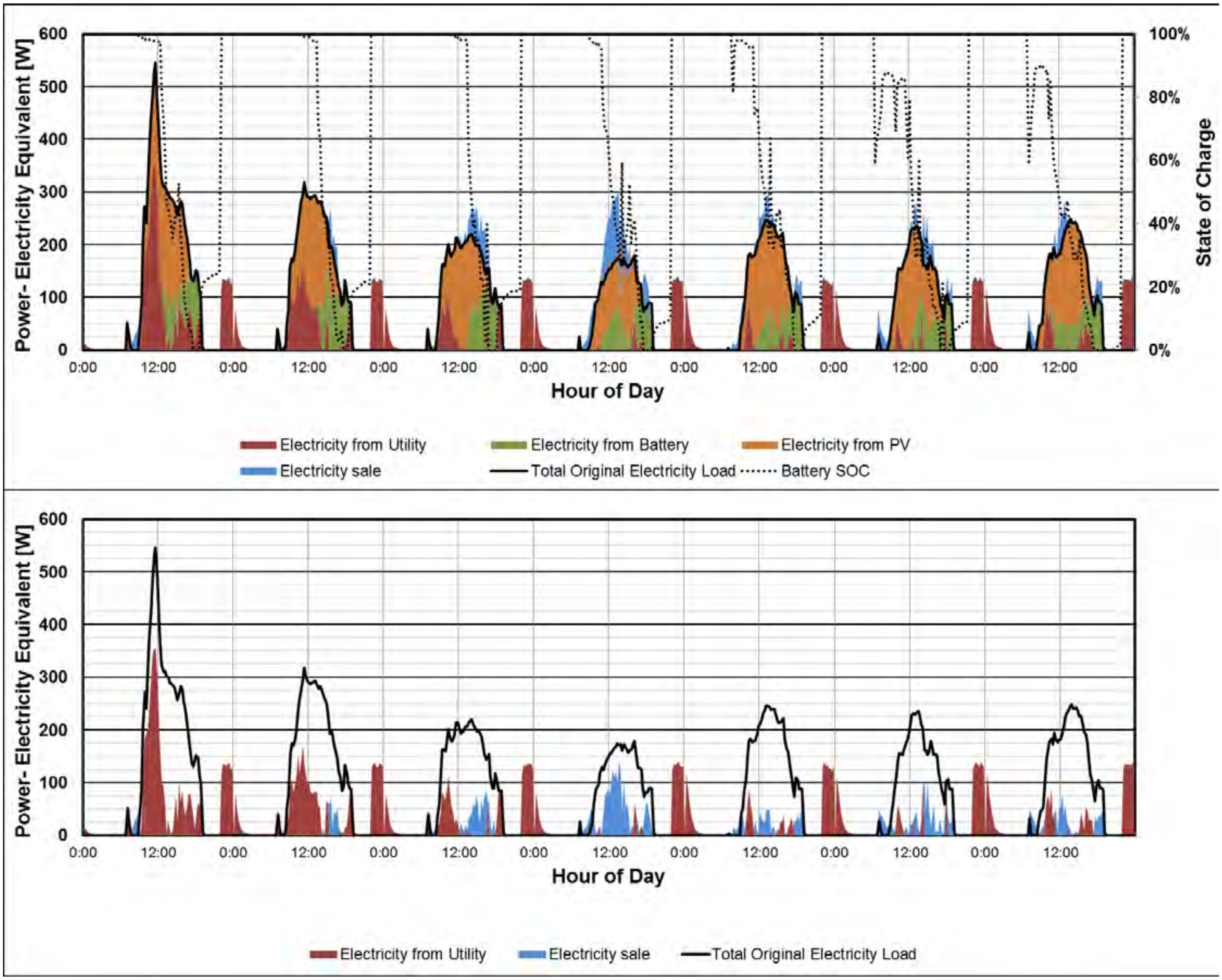



Figure 9: Above: Monitored winter electricity load profile (W) for a private office zone with a dynamic electrochromic window (SHGC=0.09-0.41, WWR=0.59) and dimmable LED lighting. The stacked bar indicates how the load is met by DER-CAMdf optimal control of the DC DER grid consisting of a 270 Wp photovoltaic panel, 540 Wh battery storage, and the utility grid with an objective of minimizing time-of-use electricity cost. The battery's estimated state of charge is given on the second y-axis. (b) Below: Monitored electricity load profile (W) for the same condition as (a) showing utility energy use and PV electrical sales back to the utility. Data are given for a 13.9 m2 south-facing perimeter office in Berkeley, California for February 20-26, 2015.

## Year 2015

### OBJECTIVES

- Address practical operational optimization issues associated with integrated demand (façade, lighting, HVAC end uses) and supply side (PV, storage, absorption cooling, etc.) control in real world buildings
- Evaluate the scalability and robustness of the control solution in collaboration with industry partners for potential application on a demonstration project in CERC 2.0

### SUMMARY OF TASKS

- Integrated demand/ supply side controls
- Developed and tested a distributed control system architecture that uses a supervisory controller to perform optimization at the whole building-to-grid level over a long period (e.g., 24-h or 7-day prediction horizon based on forecasted weather data), then uses the results of this optimization as constraints for zone-level controllers that perform short-term real-time (STRT) optimizations (e.g., 1-min control based on actual weather data)

- Integrate efficient gradient-based optimization methods based on collocation method and state estimation techniques based on Unscented Kalman Filter to the control system architecture
- Deploy the system architecture using Dockers containers (https://www.docker.com/whatisdocker) for scalability and reusability

**MAJOR FINDINGS AND OUTCOMES**

- Integrated demand/ supply side controls
- The prototype control system architecture was tested for a subset of a commercial building that has west- and east-facing rooms and that was emulated in Modelica. The building emulator, state-, and disturbance-estimator, weather emulator, optimization, and data bases were integrated. End-to-end runs were conducted that included the building emulator, state estimation, and optimization
- Application of the control system architecture on a commercial building in simulation led to about 10% energy savings compared to a baseline with traditional PI controllers
- All software used is open-source and free available, except for one which we used to export the model that is used for the emulator. However, DOE is currently redesigning EnergyPlus to have Modelica tightly integrated for the HVAC and control simulation. When this technology is in place, it will be possible to also use the system architecture with free open-source tools only
- Virtualization of the system architecture through Dockers allows to easily instantiate and deploy new MPC instances. This makes the infrastructure scalable and reusable

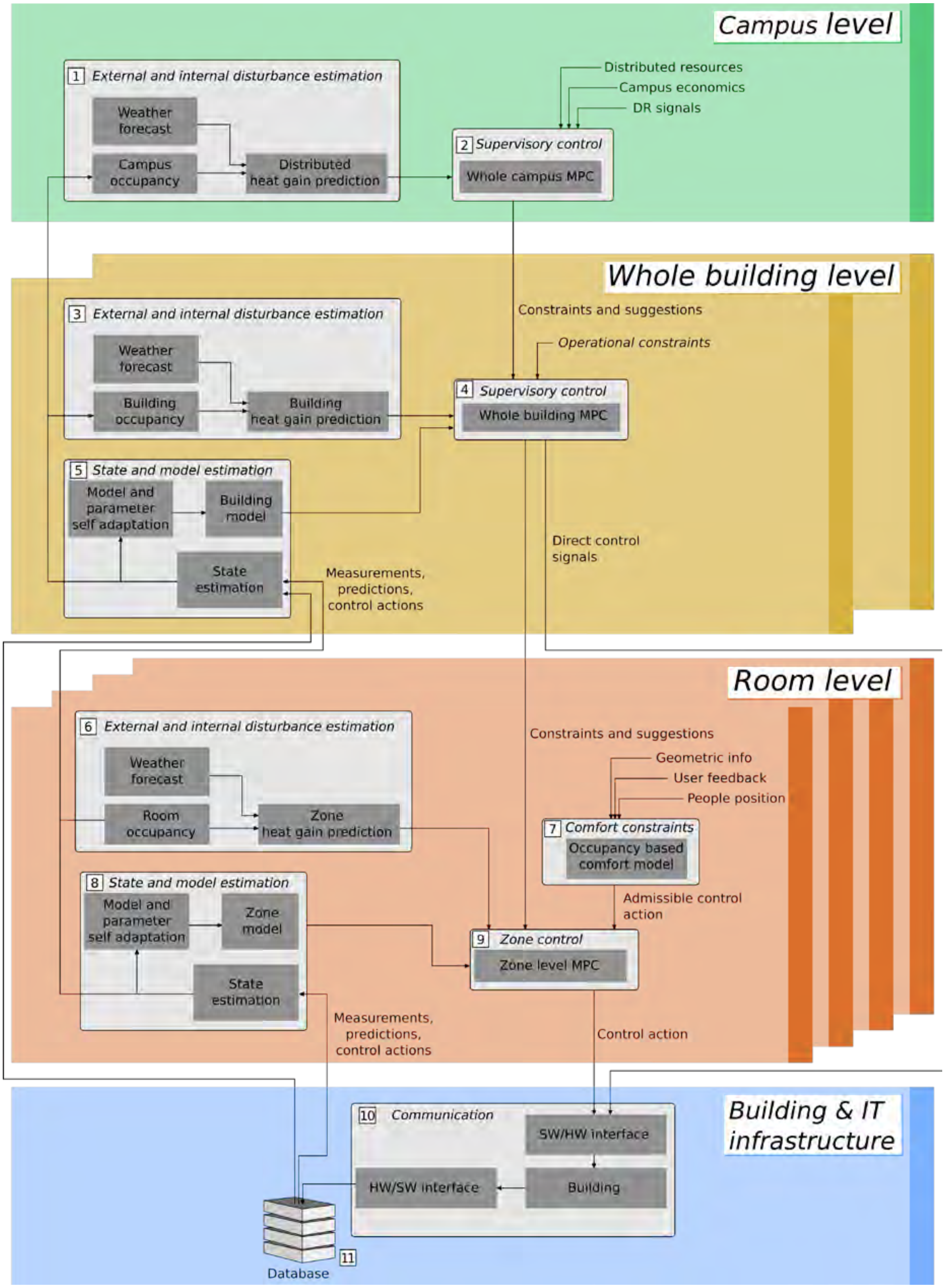



**Figure 10: Architecture of the distributed room level MPC controller.**

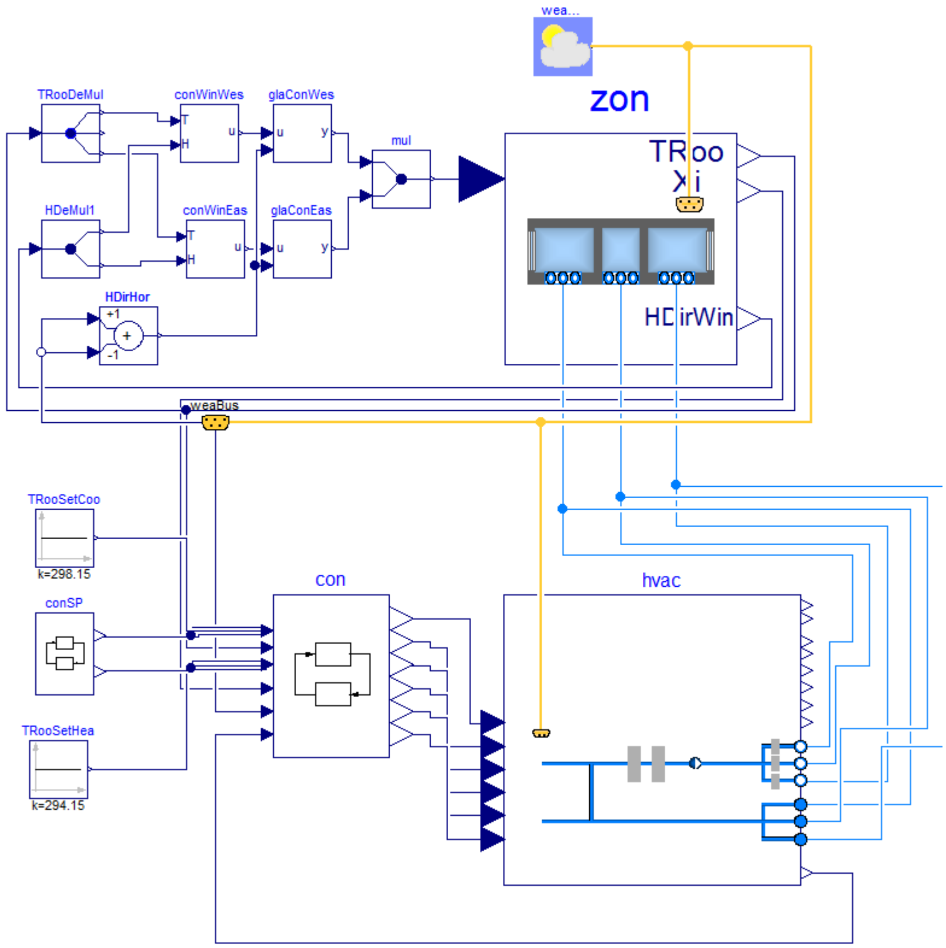



Figure 11: Modelica model of the detailed model that is used as the emulator. On the left are the input signals of the MPC controller, which then are processed into set points for heating and cooling temperatures (in order to have a dead-band that allows for free-floating despite model mismatch). The block con contains the controller of the HVAC system, the block hvac contains the VAV system, the block zon contains the three thermal zones and the block weaDat is the TMY3 weather data reader. On the right hand side are various blocks for post-processing and to output signals that are then used by the MPC.

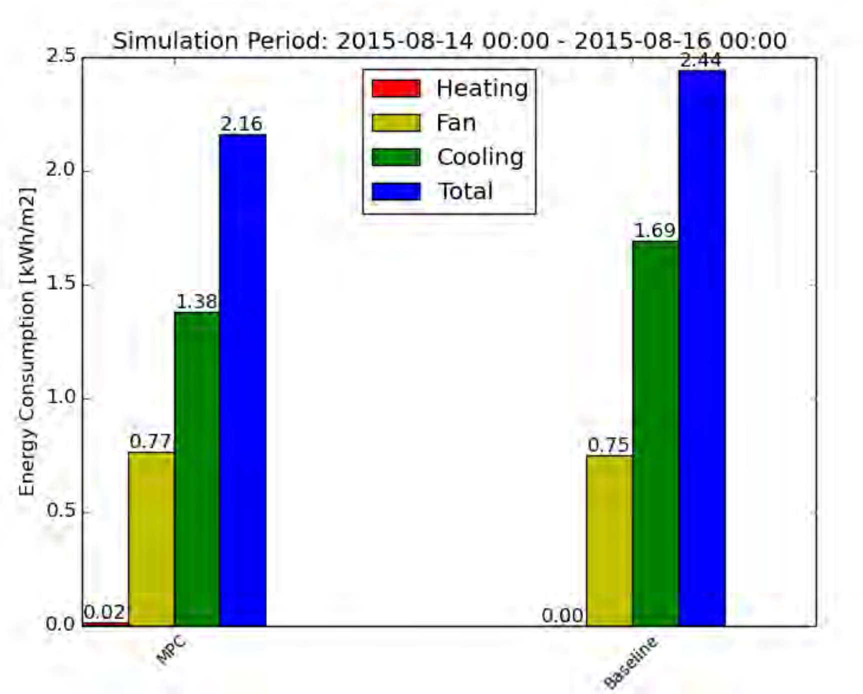



Figure 12: Energy consumption for the baseline and the MPC for two days of simulation.

## Major Outcomes and Achievements

### Products Launched

- Sage Electrochromics, first monitored demonstration in China; modified controls based on monitored field study at LBNL
- Lutron Electronics, modified controls based on monitored field study at LBNL

### Standards, Codes, and Policies influenced

- China's adoption of ISO 15099; all major Chinese manufacturers now use the standardized procedures for measurement of specular glazings and contribute their spectral data for inclusion in the IGDB

### List of Publications

- Lee, Eleanor S., Christoph Gehbauer, Brian E. Coffey, Andrew McNeil, Michael Stadler, Chris Marnay; Integrated control of dynamic facades and distributed energy resources for energy cost minimization in commercial buildings; Solar Energy 122 (2015): 1384-1397.
- Lee, Eleanor S., Xiufeng Pang, Andrew McNeil, Sabine Hoffmann, Anothai Thanachareonkit, Zhengrong Li, Yong Ding; Assessment of the potential to achieve very low energy use in public buildings in China with advanced window and shading systems, Buildings 2015, 5(2): 668-699.
- Zhengrong Li, Junling Ju, Weipeng Xu, Daylighting Control Performance and Subject Responses to Electrochromic Windows in a Meeting Room, Procedia Engineering, Volume 121, 2015, Pages 27-32, ISSN 1877-7058.
- Wetter, Michael, Marco Bonvini, Thierry Stephane Nouidui, Equation-based languages - A new paradigm for building energy modeling, simulation and optimization, Energy and Buildings 117, September 2015, doi: 10.1016/j.enbuild.2015.10.017.

## Collaboration

Provided technical support to industry primarily to enable equitable comparison of glazing and complex fenestration products using international standards, development of new prototype technologies by industry, and provision of third-party field measured data demonstrating the performance impacts of emerging technologies. Collaborations with industry initiated in Years 4-5 related to integrated controls will continue in CERC 2.0.

Collaborated with the Chinese glass industry to ensure that Chinese products were included in the international glazing database. Manufacturers will continue to submit their data to LBNL as new products are developed. Provided training on LBNL software tools; a Chinese version of LBNL's WINDOW tool was created then disseminated in China. Collaborated with Tongji University on a demonstration project involving smart windows. Shared monitoring protocols, survey tools, and analysis techniques with academic and industry researchers.

## Conclusions

Industry has many innovative window and shading technologies that have the technical potential to reduce energy use in both the U.S. and in China. Efforts within this project to standardize methods used to characterize the performance of glazing and shading systems will enable equitable product comparisons of both U.S. and China products world- wide. Research to evaluate and improve upon the performance of emerging prototype technologies was conducted in full-scale test facilities at LBNL and at SGRS-Shanghai, leading to products that are more thoroughly vetted prior to release into the market. Exploratory work was conducted to develop a hierarchical controls framework with which to optimize operable fenestration systems in concert with other building systems (lighting, HVAC, plug loads) and supply side resources. The value proposition for the basic component technology (motorized shading, switchable windows) can therefore be expanded to a broader context for greater impact and resilience, supporting the goal of zero net energy defined by both the U.S. and China.

# Materials that Improve the Cost-Effectiveness of Air Barrier Systems

***Joint Project***

## U.S. Partners

- Oak Ridge National Laboratory
- Dow Chemical
- 3M

## China Partners

- China Academy of Building Research

## Overview

ORNL, Dow Chemical, and 3M collaborated on the development and evaluation of two new technologies that aimed to improve the airtightness of buildings while making the installation of their products easier and faster than what was available in the market. Two products emerged from this project: Dow's LIQUIDARMOR and 3M 3015 primer-less self-adhered membrane. LIQUIDARMOR was installed in a small section of the China Academy of Building Research; findings indicate that the air leakage rate from the area where typical construction practices were followed was ~20% higher than the value obtained from the area that utilized LIQUIDARMOR. Additionally, funds from CERC-BEE and the Air Barrier Association of America were combined to develop an online calculator that estimates energy savings from improvements in airtightness in several cities in the US, China, and Canada. This tool will be free to the public and will be available in the fall of 2016.

## Research Objectives

The main objective of this multi-year project was for ORNL, Dow and 3M to develop and evaluate the performance of materials that ease the installation of air barriers on building envelopes. More specifically,

- Dow and ORNL collaborated on the only sprayable liquid flashing (LF) that decreases installation time by up to 75% when compared to tapes
- 3M and ORNL collaborated on a primer-less self-adhered membrane that decreases installation time by up to 50% when compared to asphalt-based membranes that require a primer

## Major Accomplishments

Launching Dow's LIQUIDARMOR, 3M 3015, and the online airtightness savings calculator.

## Summary of Research Activities

### Year 2013

**OBJECTIVE**

- Develop a test protocol to evaluate the performance of air barriers using a large-scale environmental chamber

**SUMMARY OF TASKS**

- ORNL developed a test procedure to evaluate the performance of air barriers in consultation with Dow. The procedure involves air and water penetration tests before and after the air barrier has been aged through pressure and temperature cycles
- ORNL, Dow, 3M and CABR coordinated the installation of LIQUIDARMOR and 3M 3015 at the CABR building in Shanghai

**MAJOR FINDINGS AND OUTCOMES**

- ORNL programmed its environmental chamber to be able to conduct the tests specified in the developed procedure
- LIQUIDARMOR and 3M 3015 were installed in small areas of the CABR building

## Year 2014

**OBJECTIVE**

- Evaluate the performance of LIQUIDARMOR and 3M 3015 using the developed lab test protocol

**SUMMARY OF TASKS**

- ORNL tested the performance of LIQUIDARMOR on THERMAX and DensGlass
- ORNL tested the performance of 3M 3015 on DensGlass
- Dow and 3M generated a technical product planning roadmap
- ORNL initiated discussion with the developer of the Singyes and Wuhan Rixin buildings to determine if either LIQUIDARMOR or 3M 3015 could be installed in these buildings

**MAJOR FINDINGS AND OUTCOMES**

- Dow launched LIQUIDARMOR – RS (residential version) and LIQUIDARMOR – CM (commercial version)
- LIQUIDARMOR on THERMAX and DensGlass successfully met the performance criteria that were set for the lab tests
- 3M 3015 on DensGlass successfully met the performance criteria that were set for the lab tests
- Tests that were conducted at the CABR building indicate that the area where LIQUIDARMOR was used had a leakage rate that was 20% lower than that of the area where typical construction practices were followed. Difficulties were encountered with the installation of the 3M product; therefore, leakage rates were not collected from this area
- After multiple email exchanges between ORNL and Singyes, both parties determined that neither LIQUIDARMOR and 3M 3015 were not suitable for this buildings

## Year 2015

### OBJECTIVE

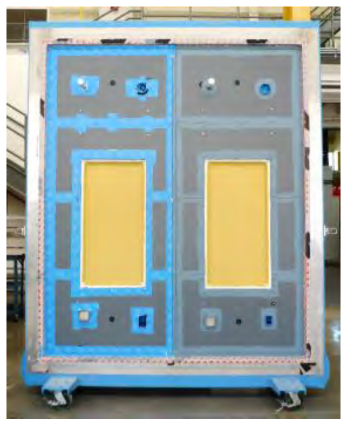
- Continue evaluating the performance of LIQUIDARMOR and 3M 3015 using the developed lab test protocol

### SUMMARY OF TASKS

- ORNL tested the performance of LIQUIDARMOR over DensGlass and THERMAX with ¼" gaps, and in a side-by-side comparison with tape
- ORNL tested the performance of 3M 3015 on Durock, and of 3M 3015VP over DensGlass
- ORNL attempted to find other demonstration buildings in China

### MAJOR FINDINGS AND OUTCOMES

- LIQUIDARMOR over DensGlass and THERMAX with ¼" gaps successfully met the performance criteria that were set for the lab tests
- Side-by-side comparison of LIQUIDARMOR with tape demonstrated that LIQUIDARMOR is faster to install and performed better than tape. More specifically, the part of the test wall that used tape had several water leaks
- LIQUIDARMOR was installed on buildings around the country
- 3M 3015 on Durock and 3M 3015VP on DensGlass successfully met the performance criteria that were set for the lab tests
- 3M 3015 was installed primarily in the northeast area




## Major Outcomes and Achievements

- Won the 2016 Gold Edison Award for Building Construction & Lighting Innovations
- Finalist for R&D100 in 2015

### Products Launched

- Dow Patent: Method for sealing fenestration openings. US 8641846 B2
- Dow's LIQUIDARMOR – RS
- Dow's LIQUIDARMOR – CM
- 3M 3015 primer-less self-adhered membrane
- 3M 3015VP vapor permeable primer-less self-adhered membrane
- Online Airtightness Savings Calculator for the US, Canada and China (In progress. Sponsored by the Air Barrier Association of America and CERC-BEE)
- MoHURD issued in November of 2015 technical guidelines for passive housing (http://www.mohurd.gov.cn/wjfb/201511/t20151113_225589.html) where the use of a continuous air barrier is recommended

### Workshops

- Dow hosted numerous installation trainings around the country
- 3M hosted numerous installation trainings around the country

### List of Publications

- Shrestha S, Hun DE, Ng L, Desjarlais AO, Emmerich S, Dalgleish L. 2016. Online Airtightness Savings Calculator for the US, Canada and China (under peer review). Buildings Conference XIII; Clearwater, FL

## Collaboration

- ORNL, Dow and 3M primarily collaborated on lab evaluations and attempting to find demonstration buildings in China
- ORNL and Dow participated in the first cohort of DOE's Lab-Corps. ORNL greatly benefitted from the expertise of our industry mentor, Linda Jeng, on the technology to market process
- ORNL and 3M were invited to jointly present in the 2015 Better Buildings Summit
- ORNL will continue collaborating with Dow Chemical and 3M under CERC 2.0
- ORNL collaborated with CABR on the installation of LIQUIDARMOR and 3M 3015 in their new building in Shanghai

## Conclusions

This project was successful in developing, evaluating, commercializing, and deploying new air barrier technologies in the US. Market penetration is challenging in China because improving airtightness is not among the popular energy efficient strategies.

# Cool Roofs & Urban Heat Islands

***Joint Project***

## U.S. Partners

- Lawrence Berkeley National Laboratory
- Dow Chemical Company

## China Partners

- Chongqing University
- Guangdong Provincial Academy of Building Research
- MOHURD Research Institute of Standards and Norms
- Institute of Atmospheric Physics Chinese Academy of Sciences
- Shenzhen IBR, Xiamen IBR, Jiangsu IBR, Sichuan IBR, Shangxi IBR, Xijiang IBR, and China Building Material Test & Certification Group

## Overview

Solar-reflective "cool" roofs are used in the U.S. and abroad to (a) decrease energy use, energy cost, and greenhouse gas (GHG) emissions via both reduced solar heat gain and lower outside air temperatures; (b) offset GHG emissions via negative radiative forcing; and (c) improve air quality and human health by reducing outside air temperatures. While the concept of reflective roofing is not new to China, broader and deeper cool roof study was needed to account for Chinese building geometry, construction, HVAC equipment, and operation; energy sources, prices, and pollutant emission factors; and climate. Prior to this project, China also did not yet have the infrastructure needed for a cool roofing market, such as cool-roof provisions in national energy efficiency standards and incentive programs, and a cool roof product rating system.

This project investigated how cool roof technology may best be adapted to Chinese climates, urban design, and building practices. We sought to quantify the potential energy and environmental benefits of cool roofs in China—especially carbon reduction—and help develop the infrastructure (including policies and rating systems) needed to promote the appropriate use of cool roofs in China. In other words, we intend to bring cool roofs in China to at least the level attained in the US, and ideally to that attained in California. This will save energy and reduce GHG gas emissions in China, and create a market in China for both U.S. and Chinese made cool roofing products.

Our approach was to (a) understand through technical exchange the state of the art of materials, measurement techniques, and energy-efficiency standards for cool roofs; (b) quantify for Chinese climates, urban design and building practices the benefits of cool roofs, such as energy savings, GHG reductions, and urban cooling; (c) assess for Chinese climates, urban design and building practices the advantages and disadvantages of cool roofs when compared to traditional roofs; (d) initiate the infrastructure needed to promote the appropriate use of cool roofs in China; and (e) design (and possibly initiate) a large-scale cool roof/cool pavement demonstration project in China. We performed this work in collaboration with researchers from four primary and seven secondary partner institutions in China.

We determined through simulations that cool roofs conserve energy, save money, and reduce emissions in all hot-summer Chinese climates, and measured cool roof savings in real buildings in Chongqing and near Guangzhou. We found that the widespread adoption of cool roofs could significantly reduce summer afternoon air temperature, especially during heat waves, in the hot and populous city of Guangzhou. We conducted a year-long experiment in Chongqing comparing black, white, and garden roofs. We started natural exposure trials in nine Chinese cities that will track the changes over time of the albedo (solar reflectance) of cool roofing products, and will eventually be used to adapt to Chinese climates LBNL's lab aging practice for roof materials. Finally, we added to national Chinese standards a credit for the use of cool roofs on residential buildings in hot summer/warm winter climates, and credits for the use of cool roof and cool wall coatings on all buildings in hot summer climates.

In addition to the above-mentioned outcomes, this project also included the development of superhydrophobic white elastomeric coatings for low slope roofs intended to be highly water resistant and solar reflective. This task was carried out through a CRADA between LBNL, Oak Ridge National Laboratory and the Dow Chemical Company. The outcomes of this CRADA have are documented in a separate final summary report.

This project helped developed the scientifically based infrastructure, including code credits and product ratings, needed to promote the climate-appropriate use of energy-saving cool roof technology in China. This creates a market for the cool roof technology (superhydrophic roof coatings) being developed in a parallel CERC activity led by Dow Chemical and ORNL.

## Research Objectives

This project sought to quantify the potential energy and environmental benefits of cool roofs in China —especially carbon reduction—and help develop the infrastructure (including policies and rating systems) needed to promote the appropriate use of cool roofs in China.

To provide the science needed to support development of cool surface credits, requirements, and ratings in Chinese building energy-efficiency standards and incentive programs, we planned to

- Simulate and measure cool roof energy savings in China.
- Demonstrate existing cool roof technology on Chinese buildings.
- Simulate the potential for cool roofs to mitigate urban heat islands (UHIs) in China.
- Measure the long-term performance (aged albedo) of existing cool roofing materials in Chinese cities.
- Calibrate to a Chinese climate LBNL's lab aging process for roofing products (ASTM D7897-15).

We also planned to collaborate with Chinese researchers and the Chinese government to develop cool surface credits based on this science.

Under this project new technology approaches are also being explored for improving water resistance of cool roof coatings with possible generation of Intellectual Property beneficial to cool roof technology for both U.S. and China. Dow researchers offer expertise in polymer design, coatings formulation and exterior durability. In this proposed program the water resistance characteristics of highly reflective commercial and experimental roof coatings will be identified with the aim of understanding the material and chemical parameters necessary for improving the long term water resistance in global environments. Understanding the effects of water (i.e. absorption, migration, permeability and adhesion), heat, light, age and UV on key long term solar reflective properties will allow the invention and commercialization of proprietary roof coating technologies. This will result in higher-performing, long-term SR technologies that can effectively double cool roof technology energy savings.

## Major Accomplishments

Cool roofs were shown to conserve energy, save money, and reduce emissions of CO2, NOx, and SO2 in all hot-summer Chinese climates. We found that the widespread adoption of cool roofs could significantly lower summer afternoon air temperature, especially during heat waves, in the hot and populous city of Guangzhou. Natural exposure trials underway in nine Chinese cities will assess the long-term performance of cool roofing product in China, and permit adaptation to China of LBNL's lab aging practice for roofing materials (ASTM D7897-15). We added to national Chinese standards a credit for the use of cool roofs on residential buildings in hot summer/warm winter climates (2012), and credits for the use of cool roof and cool wall coatings on all buildings in hot summer climates (2015).

## Summary of Research Activities

### Year 2011

**OBJECTIVES**

- Develop a US-China joint workplan to assess how cool roof technology may best be adapted to Chinese climates, urban design, and building practices
- Foster technical exchange and collaboration between U.S. and Chinese cool roof stakeholders, including researchers, rating bodies, government officials, and manufacturers
- Quantify the potential energy and environmental benefits of cool roofs in China—especially carbon reduction
- Help develop the infrastructure (including policies and rating systems) needed to promote the appropriate use of cool roofs in China

**SUMMARY OF TASKS**

*CERC workplan development*

Following a series of meetings in both countries, U.S. and Chinese CERC cool roof researchers, in consultation with DOE and MoHURD, developed an eight-task joint research plan including (1) a cool roof literature survey, cool roof experiments in two Chinese cities, and a black/white/garden roof comparison in China; (2) investigating methods used to calculate GHG emission reductions and offsets from cool roofs, and their application in China; (3) collecting China-specific input data needed to evaluate cool roof benefits of cool roofs in China; (4) using these inputs to assess cool roof benefits in China; (5) comparing cool roofs to traditional roofs in China; (6) proposing measurement techniques to identify and market cool roof in China; (7) proposing model codes for cool roof incentives/requirements in China; and (8) designing a large-scale cool roof experiment in China.

*Technical exchange and collaboration*

Researchers and officials from LBNL, DOE, MOHURD, the (US) Cool Roof Rating Council (CRRC), Guangdong Provincial Academy of Building Research (GPABR), South China University of Technology (SCUT), Fujian Provincial Academy of Building Research (FPABR), China Academy of Building Research (CABR), Shenzhen Institute of Building Research (SIBR), and the China Building Material Test and Certification Center (CBMTCC) convened in Shenzhen in October 2010 (Figure 1) and May 2011 (Figure 2).

GPABR demonstrated its radiative property measurement facilities to LBNL and other US visitors in May 2011.

Researchers from GPABR attended the International Cool Roof Training Workshop at LBNL in February 2011 to learn about the measurement of cool roof properties, the cool roof rating process in the US, and urban heat island mitigation programs from LBNL, the CRRC, the California Energy Commission (CEC), and the Global Cool Cities Alliance (GCCA) (Figure 3).

In May 2011, LBNL presented a day of talks in Beijing on the science, technology and benefits of cool roofs to members of the China National Building Waterproofing Association (CNBWA), an organization of Chinese roof coating manufacturers; members of the Suzhou Test Center, which measures roofing properties; and members of Dow Chemical, an industrial partner in US-China CERC-BEE (Figure 4).

In July 2011, researchers from GPABR and MOHURD's Research Institute of Standards and Norms (RISN) attended the International Workshop on Advances in Cool Roof Research, a two-day workshop in Berkeley hosted by LBNL's Heat Island Group.

*Quantifying cool roof benefits*

In summer 2011, GPABR measured the effect of a cool roof coating on the air temperature inside a factory near Guangzhou (Figure 5), while a team of Chinese researchers led by RISN measured cool roof energy savings in Guangzhou, Nanjing, and Beijing.

*Cool roof codes and policies*

The US-China Cool Roof Working Group drafted a plan to develop a cool roof rating system for China.

**MAJOR FINDINGS AND OUTCOMES**

Collaboration among more than 10 Chinese and U.S. institutions yielded a plan for US-Chinese cool roof research in CERC, as well as a plan for development of a Chinese cool roof rating system.

LBNL and CRRC taught cool roof researchers from GPABR how to measure and rate the performance of cool roofing products.

Concerns from MOHURD about the potential for cool roofs to reduce substantially the availability of space for PVs on Chinese buildings were addressed through extensive discussions among US researchers, Chinese researchers, and MOHURD officials. This kept cool roofs in CERC, with Chongqing University (CU), GPABR, and RISN as LBNL's primary partners.

(a)

(b)

**Figure 1: Chinese researchers from RISN and the Guangdong Provincial Academy of Building Research (panel a, at left) visit LBNL in Feb 2011 for cool roof training. Some of the instruments and samples are shown in panel b.**

**Figure 2: Participants at daylong presentation by Berkeley Lab to the China National Building Waterproofing Association in Beijing China in May 2011. The workshop was organized by Dow Chemical.**

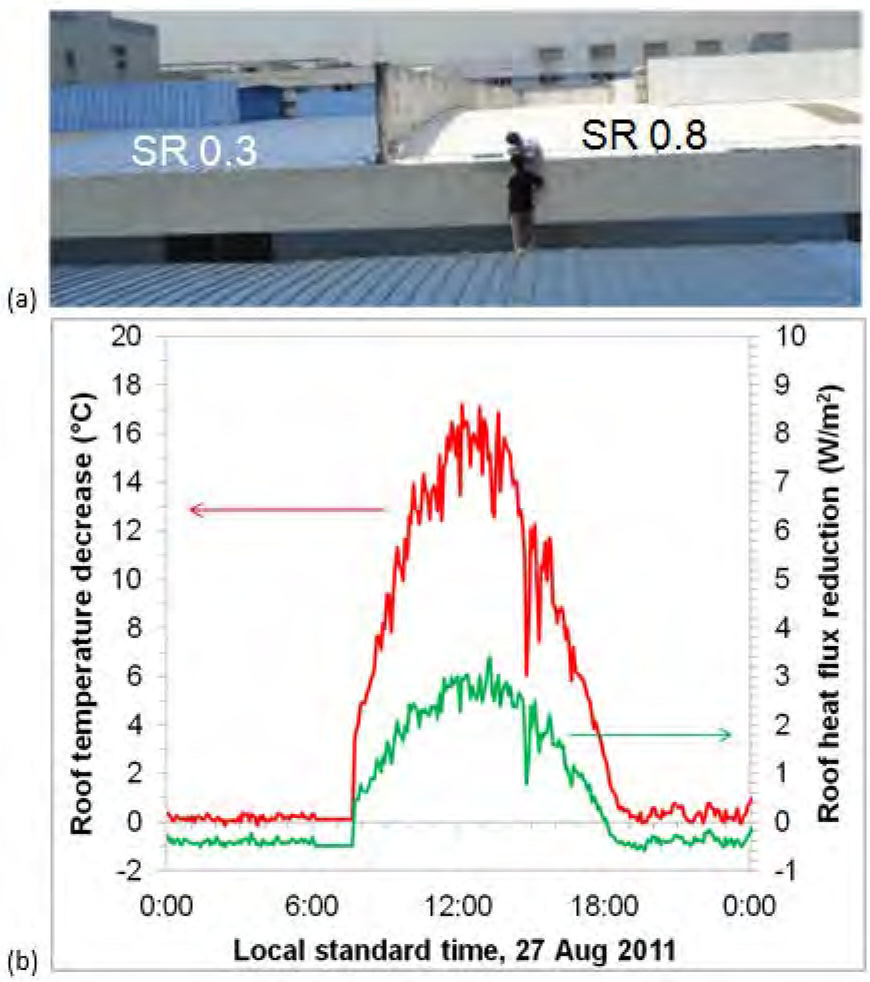



**Figure 3: In August 2011, GPABR conducted a cool roof experiment on an unconditioned factory building in Guangdong province (panel a). It showed that a white coating lowered roof temperature by about 17 °C, and decreased daily roof heat flux by about 65% (panel b).**

## Year 2012

**OBJECTIVES**

- Simulate cool roof energy savings in China
- Measure cool roof energy savings in China
- Review cool surface provisions in local and national Chinese building energy standards
- Add new cool surface credits where possible

**SUMMARY OF TASKS**

*Cool roof simulation*

CU and LBNL simulated and analyzed the annual source energy, energy cost, and emission savings attainable by applying cool roofs to office and residential buildings in seven Chinese cities. This effort included a six-day visit to CU by Levinson (LBNL) in December 2012 to collaborate with the CU researchers on this activity, and the next.

*Cool roof measurement*

CU and LBNL measured and analyzed the daily air conditioning energy savings attained by applying a cool roof to an office building on the CU campus in summer 2012. Interior air temperature reductions were also measured on days when the air conditioned was turned off.

*Energy efficiency standard review*

LBNL reviewed roof and wall requirements in five national and nine local Chinese building energy standards to identify existing cool surface credits or guidance.

**MAJOR FINDINGS AND OUTCOMES**

Simulations showed that cool roofs saved energy and money, and reduced emissions of CO2, NOx, and SO2, in all hot-summer Chinese climates. Figure 6 shows savings in annual energy cost and CO2 emissions.

The CU cool roof experiment demonstrated a 9% reduction in the daily cooling energy use of a top-floor room in an office building (Figure 7).

The review of cool surface provisions found cool roof and/or cool wall credits in existing local Chinese building energy standards in Chongqing, Shanghai, and Hainan.

In a first for national energy efficiency standards in China, RISN added cool roof credits to the national energy efficiency standard for residential buildings in hot summer and warm winter zones.

A landmark journal article detailing these results was published in Energy Policy in 2014 (Gao et al. 2014).

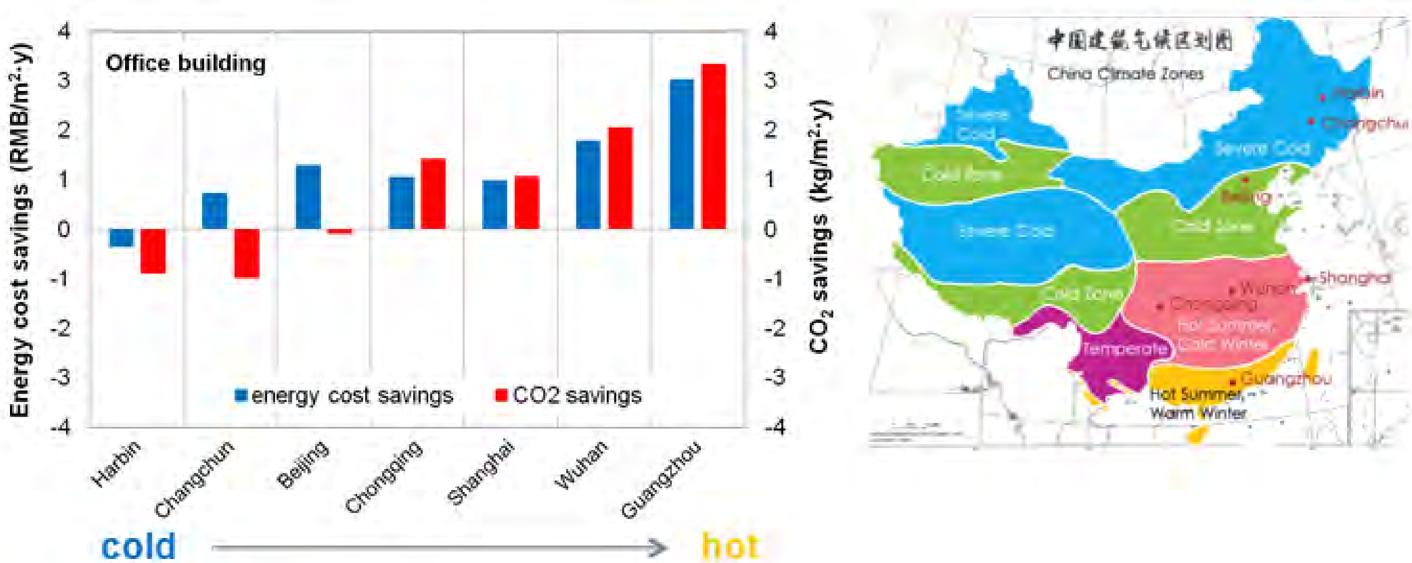



**Figure 4: Simulations by CU and LBNL showed that cool roofs reduce annual energy cost and emissions of CO2, NOx, and SO2 in all hot-summer Chinese climates.**

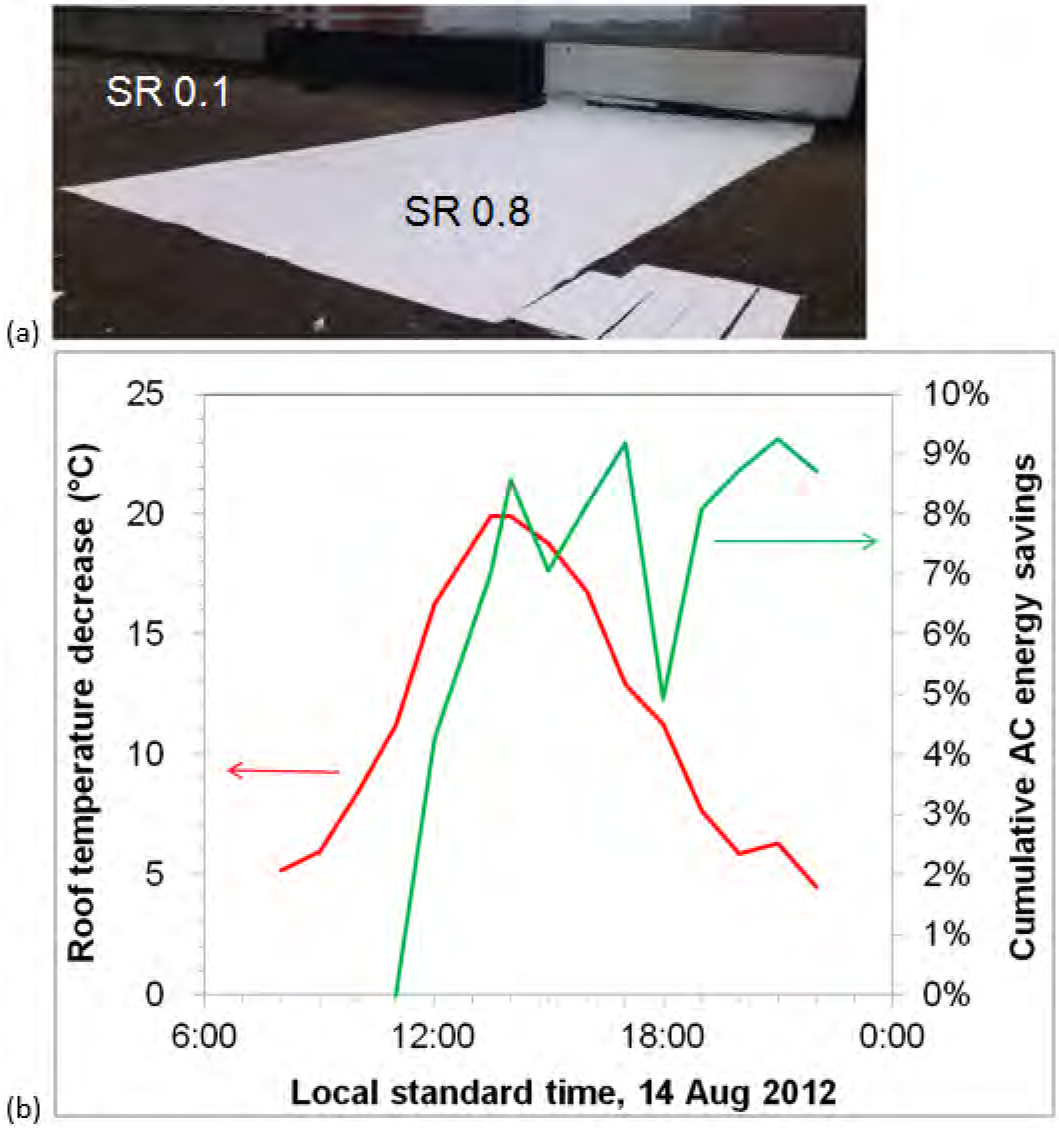



Figure 5: In August 2012, CU conducted a cool roof experiment on a conditioned office building in Chongqing (panel a). It showed that a white coating lowered roof temperature by about 20 °C, and reduced daily cooling energy use by about 9% (panel b).

## Year 2013

**OBJECTIVES**

- Advance a cool roof rating system in China
- Initiate a long term (one year) experiment comparing gray, white, and black roofs in an office building in a hot-summer Chinese city
- Initiate mesoscale modeling of the urban heat island mitigation by cool roofs in a hot-summer Chinese city
- Development of environmentally friendly, superhydrophobic (SH) based, anti-biofouling white cool roof coatings for heat island mitigation in China and US

**SUMMARY OF TASKS**

*Cool roof rating system*

In January 2013, LBNL, CRRC, CEC, and GCCA hosted a daylong cool roof workshop at LBNL for 30 members of the Chinese National Building Waterproofing Association, which represents Chinese roofing manufacturers.

In July 2013, FPABR hosted a workshop in Xiamen to determine an equivalent thermal resistance for reflective roof and wall surfaces. LBNL and many Chinese building research institutes (BRIs) participated.

*Long-term black/white/garden roof experiment*

The start of this activity was delayed by lack of funding for the Chinese researchers. However, LBNL, GPABR, and CU met in Wuhan in October 2013 to design black/white/garden roof experiments in both Chongqing and Guangzhou.

*Mesoscale modeling of UHI mitigation*

In August 2013, Millstein (LBNL) visited Cao (IAP) in Beijing for a week to initiate mesoscale modeling of potential UHI mitigation by the widespread use of cool roofs in Guangzhou.

*Development of white cool roof coatings*

ORNL and Dow personnel continued to hold detailed technical discussions on the SH powder formulations, methods to incorporate these powders, mixture fabrication and coating testing procedures. ORNL and LBNL personnel gave a joint cool roofs presentation to the U.S-China CERC-BEE Research/Demonstration Workshop in Wuhan in late October. Hunter and fellow ORNL meeting attendees visited the new Chinese Academy of Building Research (CABR) research facilities, presently under construction in Beijing, where the implementation of various energy efficiency technologies were discussed. ORNL researchers evaluated and discussed with Dow personnel the superhydrophobic extenders (SHE) mixing and dispersability studies performed by Dow. Based on these discussions, ORNL fabricated new silica based SHE powders with different shapes and structural dimensions.

ORNL initiated several anti biofouling studies using solvent-based water repellent SH coatings, and developed an accelerated microbial testing protocol and test facility to test proposed new modified SH materials and coatings. ORNL and Dow personnel had detailed technical discussions on SH powder formulations manufacture and testing. ORNL initiated several new anti biofouling studies using surface modified SH. These studies are summarized as follows:

*Accelerated Microbial Aging Protocol*

- ORNL developed a mixture of microbial species for accelerated aging test on cool roof samples
- The test protocol has shown to be capable of reducing optical performance of cool roofs equivalent to that required by EPA EnergyStar® and only in a couple of months much shorter than 3 years
- The protocol will benefit from more tests on different cool roof coatings and substrates
- A manuscript has been submitted to Energy and Building for publication consideration, and a provisional patent was filed by ORNL in February 2014

The microbial aging procedure is summarized in the flow chart in Figure 6.

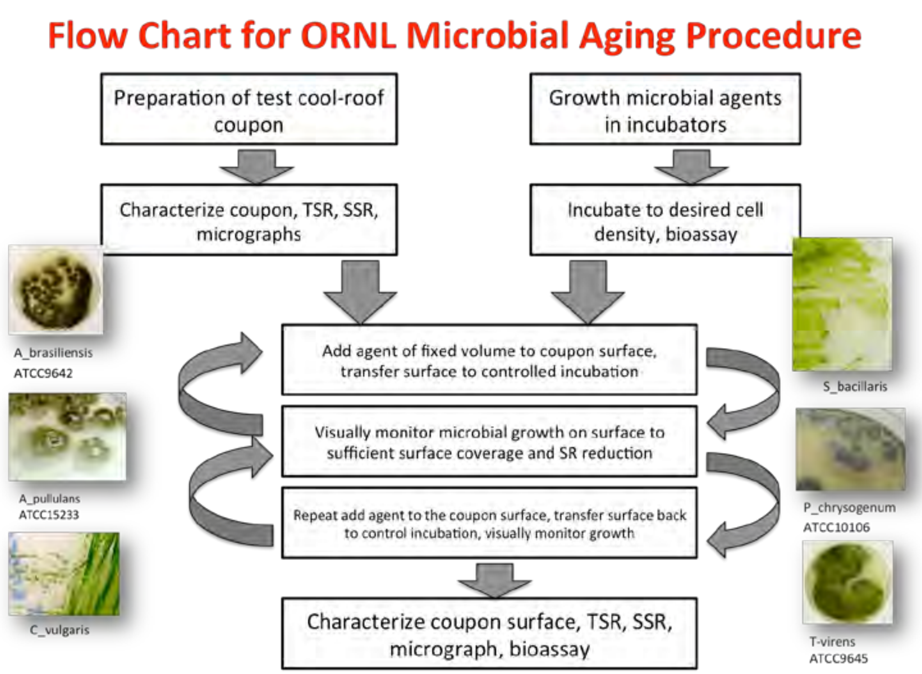



**Figure 6: Microbial aging procedure developed at ORNL.**

The results of the microbial aging studies are:

- Formation of Biofilm on Cool Roof Coating is ubiquitous, independent of surface
- Biofilm can degrade optical performance of cool roof surfaces
- It does not have to destroy the coating or coating structure to degrade the optical performance
- Preliminary tests on solvent-prepared SH coatings showed that the original ORNL microbial aging protocol could be applied
- Biofilm was successfully grown on the surfaces of the SH coating in two-three weeks, and the biofilm growth continued under proper incubation condition
- Biofilm growth was confirmed within two weeks. Reduction in solar reflectance (measured by D&S reflectometer) varied widely from a few percent to 19% at the end of two months of exposure
- SH silica particle coated surfaces were found to be microscopically transformed by microbial mixture similar to other coated surfaces

*Complete formulation and SH testing of basic formulations and coatings*

LBNL and ORNL evaluated solvent based SH anti-soiling coatings fabricated by ORNL to understand anti-soiling and microbial growth properties of very water repellent surfaces.

*Evaluate the anti-soiling ability of SH coatings*

The hydrophobicity, anti-soiling, and aging properties of the Dow fabricated coatings were evaluated at ORNL, LBNL and Dow. The coatings were found to have low hydrophobicity due to the SH silica particles being fully encapsulated in the polymer matrix. In contrast, the very SH solvent based coatings provided by ORNL were found to have significant anti-soiling behavior in the LBNL tests.

*Characterize surface roughness and topographical features, perform depth profiling measurement of water retention and coating oxidation*

Surface roughening and abrasion studies performed at LBNL on the Dow provided anti-soiling coated coupons showed increased hydrophobicity and surface roughening as some of the buried SH silica particles were exposed at the coating surface. The studies continued at ORNL and LBNL.

*Measurement of water contact angle and accelerated durability testing*

ORNL and Dow Chemical prepared anti-soiling coated coupons containing varying concentrations of SH silica powders. These coupons were evaluated at LBNL, along with reference materials, to simulate field exposure for different time lengths (3 years and 5 years).

**MAJOR FINDINGS AND OUTCOMES**

All coatings had very high dirt resistance and excellent strength, but poorer than expected water repellency and swelling due the encapsulation of the silica particles within the resin matrix.

## Year 2014

**OBJECTIVES**

- Complete the mesoscale modeling of UHI mitigation in Guangzhou begun in 2013
- Conduct the long-term gray/roof/garden roof experiment(s) designed in 2013
- Support development of a Chinese cool roof rating system by assessing the initial and aged radiative properties of typical cool roofing products in China through natural exposure trials

**SUMMARY OF TASKS**

*Mesoscale modeling of UHI mitigation*

Cao (IAP) visited LBNL for a month in May 2014 to collaborate with Millstein (LBNL) on mesocale modeling. Modeling and analysis were completed by end of year (Figure 8).

*Long-term black/white/garden roof experiment*

After securing alternative funding, CU began its long-term (one year) black/white/garden roof experiment near Chongqing in summer 2014 (Figure 9).

*Cool roof rating system*

With detailed technical guidance from LBNL, RISN and a large consortium of Chinese BRIs initiated natural exposure trials for roofing product materials at nine sites in China (Figure 10). The trials will test cool roof coatings from five manufacturers for up to five years.

*UV weathering, water repellency and accelerated durability testing of new cool roof coatings*

Accelerated UVA exposure studies performed at LBNL on the ORNL and Dow fabricated anti-soiling coated coupons.

*Complete anti-soiling coating formulation and SH and optical testing of coatings*

Dow pursued studies to expose the SH particles at the surface of the anti-soiling coatings, minimizing the encapsulation of the silica particles within the resin.

*Measurement of water contact angle and accelerated durability testing*

ORNL and Dow Chemical prepared anti-soiling coated coupons containing varying concentrations of SH silica powders. These coupons evaluated at LBNL, along with reference materials, to simulate field exposure for different time lengths (3 years and 5 years). Mechanical abrasion studies were also performed to facilitate access of the SH silica particles at the surface of the coatings. The preliminary results from these analyses and possible further studies were discussed by LBNL, ORNL and Dow.

ORNL prepared and provided DOW with additional SH particulates based on silica. The size of the particulates varied from sub-micron to tens of microns.

**MAJOR FINDINGS AND OUTCOMES**

Mesoscale modeling indicated that the widespread use of cool roofs in Guangzhou could reduce summer afternoon air temperature by ~ 1 °C on a typical summer afternoon, and by about 50% more during a heat wave. This work—one of a limited number of studies to evaluate potential air temperature reductions from cool roof deployment in Chinese cities, and the first study to directly compare the potential air temperature reductions during historic southern China heat wave events to those during typical summer time periods—was published in Environmental Science & Technology in 2015 (Cao et al. 2015).

CU's long-term black/white/garden roof commenced, with completion scheduled for 2015.

The roofing product natural exposure trials began at nine sites in China.

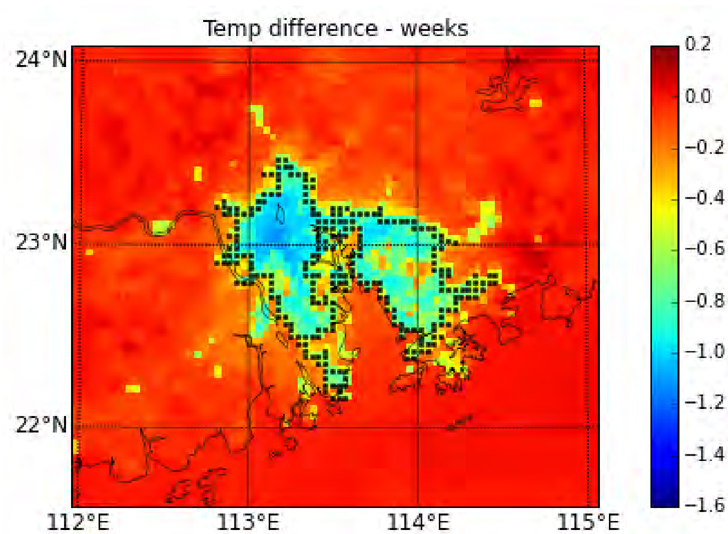



Figure 7: Climate modeling indicates widespread cool roofs could lower mid-day summer air temperatures in Guangzhou by about 1 °C.

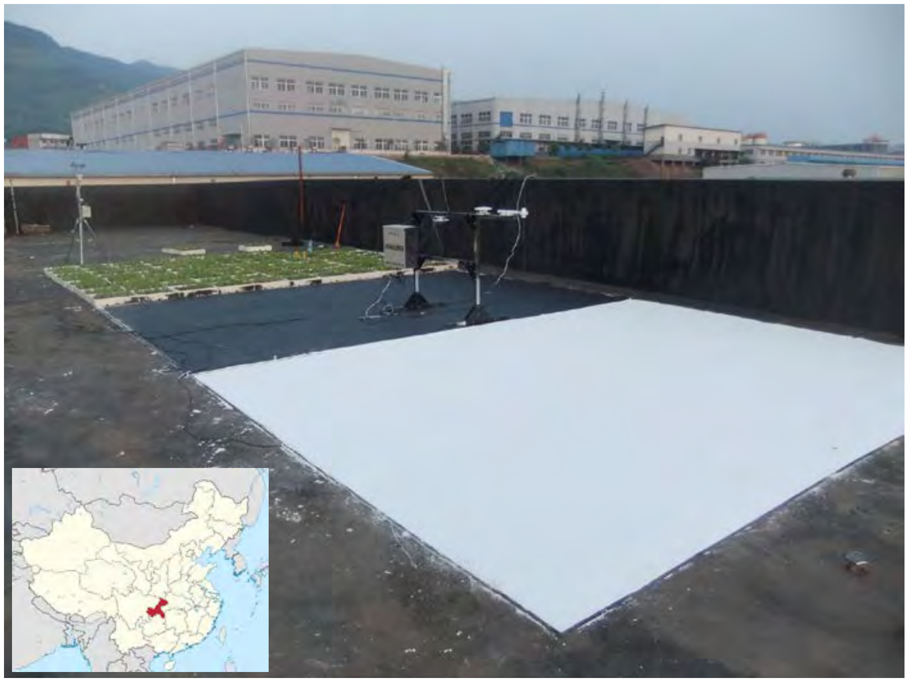


Figure 8: CU initiated its black/white/garden roof experiment near Chongqing in summer 2014.


Figure 9: RISN, LBNL, and a large consortium of Chinese BRIs started roofing product natural exposure trials at nine sites in China (panel a). Each site exposed many replicates of each product (panel b).

## Year 2015

**OBJECTIVES**

- Develop cool surface credits/requirements for Chinese buildings
- Model the UHI mitigation attainable from a large-scale (1 $km^2$) cool roof demonstration in Guangzhou
- Evaluate albedo changes at 1 year from the roofing product natural exposure trials begin in 2014
- As a proof of concept, calibrate LBNL's lab aging technique for roofing products (ASTM D7897-15) to 1-year albedo changes from natural exposure in one Chinese city
- Complete one long-term black/white/garden roof experiment in China

**SUMMARY OF TASKS**

*Cool surface credits*

LBNL reviewed the status of cool surface provisions in the building energy efficiency standards of 32 Chinese provinces.

RISN and GPABR continued to lead the effort to introduce cool roof and cool wall credits in all hot-summer Chinese climates.

*Mesoscale modeling of large-scale cool roof demonstration*

LBNL used the Weather Research and Forecasting (WRF) model to simulate the effects of a 1 $km^2$ cool roof demonstration on summer air temperature in Guangzhou, and found downwind temperature reductions up to 0.8 °C (Figure 11).

*Natural exposure trials*

In July 2015, LBNL hosted a weeklong 'International Cool Roof' workshop in which seven researchers from five Chinese building research institutes, and one researcher from RISN, learned how to measure the radiative properties of cool roofs, practiced LBNL's lab aging method for cool roofs, reviewed 6-month results from the China cool roof exposure program, and met with staff from the California Energy Commission and the Cool Roof Rating Council (Figure 12).

LBNL, RISN, and the nine Chinese research institutions conducting roofing product natural exposure trials convened in Xiamen in December 2015 to review 12-month results.

In December 2015, LBNL inspected the natural exposure sites in Xiamen and Guangzhou.

*Calibration of lab-aging method to Chinese climate*

As a proof of concept, LBNL will tune its lab aging practice to replicate albedo changes measured after one year of exposure in Guangzhou. This activity will continue through summer 2016.

*Long-term black/white/garden roof experiment*

CU continued its long-term (one year) black/white/garden roof experiment near Chongqing. LBNL visited CU in December 2015 to collaborate on the analysis and report.

Using an experimental design proposed by LBNL in 2013, GPABR initiated its long-term (one year) black/white/garden roof experiment in Guangzhou in summer 2015. LBNL visited GPABR in December 2015 to collaborate on the analysis.

Xiamen Institute of Building Research (XIBR) initiated its long-term (one year) black/white/garden roof experiment in Xiamen in winter 2015. LBNL visited XIBR in December 2015 to collaborate on the analysis.

*Development of white cool roof coatings*

ORNL synthesized superhydrophobic (SH) silica particles with controlled size and surface features. Testing coupons were coated with SH particles of different sizes and geometries. ORNL provided LBNL coated coupons for further testing. The synthesized particles are shown in Figure 10.

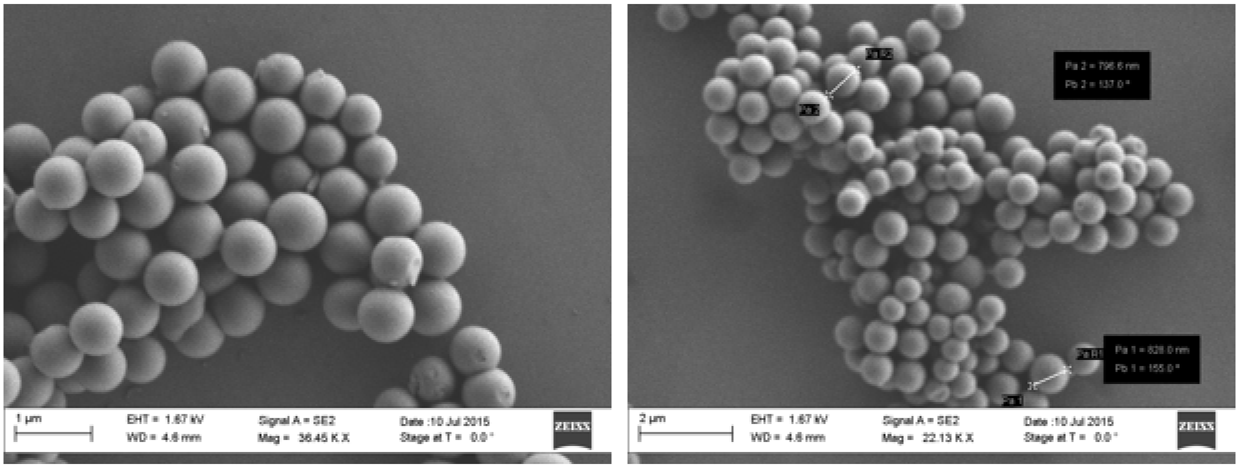



**Figure 10: Synthesized silica particles with controlled size.**

### *Evaluate commercially available DE superhydrophobic powders for cool roof application*

Dow developed several application method approaches for dispersing SH diatomaceous earth (DE) particles into a polymer matrix. ORNL prepared SH testing coupons based on commercially available DE particles of different sizes and geometries.

Evaluated the water repellency, self-cleaning ability and water permeation of the superhydrophobic coatings.

### *Preparation of samples based on SH DE particles*

ORNL synthesized and provided DOW with additional SH particulates based on silica. ORNL prepared SH testing coupons based on two different types of silica particles that were synthesized using sol-gel techniques. The powders were characterized using SEM and particle size analysis techniques. The water repellency properties of the coupons were measured using contact angle measurements. The results of Dow and ORNL indicate that the performance of the coatings is associated with the ability of the SH particles to diffuse and migrate to the top of the coating (polymer – air interface).

### *Continued accelerated coating testing and formulation optimization based on ongoing coating durability studies*

Based on LBNL's accelerated aging results ORNL fabricated a series of additional samples. The samples were shipped to LBNL for further testing.

## MAJOR FINDINGS AND OUTCOMES

The 2015 edition of the Chinese national standard 'Technical Specification for Application of Architectural Reflective Thermal Insulation Coating' (JGJ/T 359 – 2015, effective February 2016) offers credits (insulation/albedo trade-offs) for the application of these materials (a type of cool coating) to roofs and walls on both public and residential buildings in all hot-summer Chinese climates. This is a major advancement for cool surfaces in Chinese building energy efficiency standards. LBNL is preparing a report explaining the nature of the coating standard, how it will integrate with existing Chinese building energy standards, and how the ongoing natural exposure and lab aging studies can be used to enhance the next version of the coating standard.

Mesoscale modeling indicated that a large-scale (1 $km^2$) cool roof demonstration in Guangzhou could reduce downwind outside air temperature by as much as 0.8 ºC on a summer day. This indicates that such a demonstration could yield a measurable local benefit. This study will be submitted to Urban Climate in spring 2016.

Early results from the first nine months of natural exposure trials at three of the nine sites in China indicate that the albedos of white roof coatings dropped more swiftly in China than in the U.S., but may stabilize after 3 months (Figure 13). The minimum values reported to date (about 0.62) are still higher than the long-term value used to model cool roof savings (0.60).

CU completed its long-term (1 year) black/white/garden roof experiment near Chongqing, finding significant energy savings from both the white roof and the garden roof. This study will be submitted to a journal such as Energy & Buildings by summer 2016.

CU completed a short-term cool wall experiment near Chongqing, finding significant reductions in cooling load. This study will be submitted to a journal such as Energy & Buildings by summer 2016.

CU completed a modeling analysis comparing the energy savings and economics of gray, white, and garden roofs across China. This work has been submitted to the Fourth International Conference on Countermeasure to Urban Heat Islands (4th IC2UHI; Singapore, May 2016) (Gao et al. 2016a).

ORNL's synthesized particles with well-defined size and geometry, and the diameter (~800nm) of the individual particles is in good agreement with the particle size analysis measurements. The ORNL coating based on superhydrophobic (SH) particulates showed the best performance according to the LBNL testing results. According to the LBNL aging testing that is equivalent to 3 years of natural exposure (ASTM D7897) the ORNL SH coating demonstrated 3.3 and 4.9% reduction in the solar reflectance and the water contact angle, respectively. This is the best performing coating in terms of weathering durability as well as in terms of properties. The initial values of the solar reflectance and water contact angle are 0.778 and 167o, respectively. Based on these results ORNL is preparing additional samples.

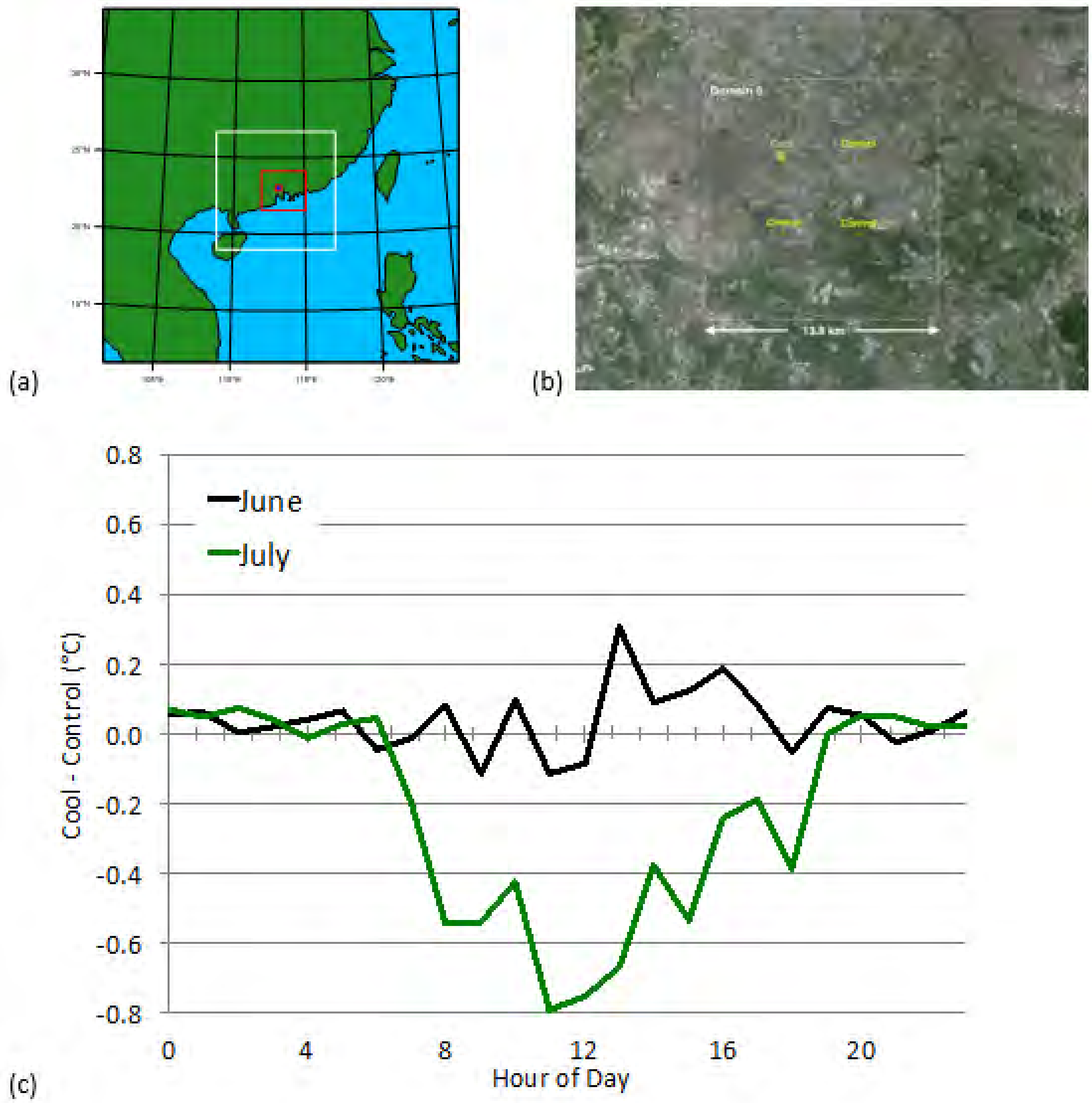



**Figure 11: Mesoscale modeling of outdoor air temperatures in Guangzhou (panels a and b) shows that assigning a high roof albedo to an approximately 1 km² "cool" cell can make its 2 m air temperature up to 0.8 °C lower than that of unmodified control cells (panel, curve marked "July"). The second curve in panel c, marked "June", shows the air temperature difference (cool – control) when the cool cell has the same roof albedo as the control cells.**


**Figure 12: Seven researchers from five Chinese institutions joined cool roof researchers from India and Italy, and LBNL staff, at the International Cool Roof Workshop at LBNL in July 2015.**

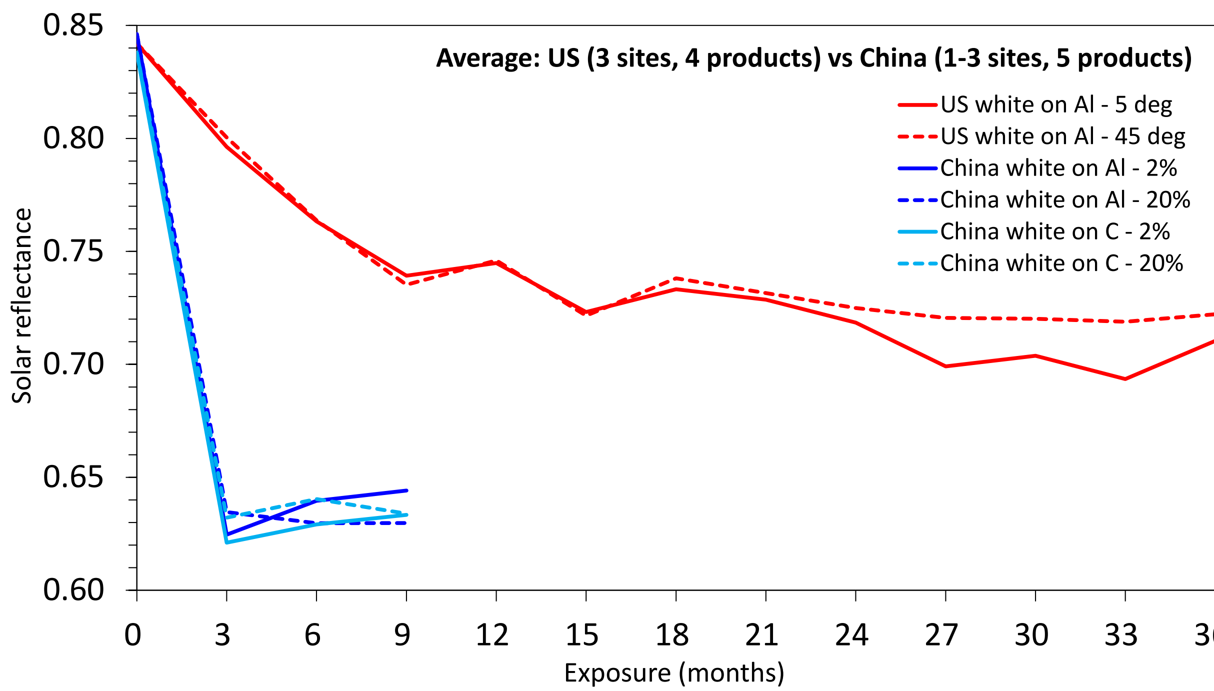



**Figure 13: Early results from the first nine months of natural exposure trials at three of the nine sites in China indicate that the albedos of white roof coatings dropped more swiftly in China than in the U.S., but may stabilize after 3 months.**

## Major Outcomes and Achievements

### Standards, Codes, and Policies Influenced

*National standard cool surface credits*

- Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zones (JGJ75-2012). This 2012 Chinese national energy efficiency standard credits the use of cool roofs on residential buildings in hot summer and warm winter climate zones.
- Technical Specification for Application of Architectural Reflective Thermal Insulation Coating (JGJ/T 359-2015). This 2015 Chinese national technical standard credits the use of cool coatings on both public and residential buildings in all hot-summer Chinese climate zones.
- Assessment Standard for Green Building (GB/T 50378-2014). This 2014 green building standard now offer 4 points in the outdoor environment category for mitigating the heat island effect.

*Local standards*

As of December 2015, eight provinces or municipalities in hot-summer regions credit cool surfaces credits in their public and/or residential building design standards. We indicate below the location, climate, and year that credits first appeared. Seven local standards have added cool surface credits since the US-China Cool Roof Working Group first met in October 2010.

- Chongqing (hot summer/cold winter): public 2013, residential 2010
- Sichuan Province (hot summer/cold winter, cold, temperate): residential 2012
- Fujian Province (hot summer/cold winter, hot summer/warm winter): residential 2014
- Guangdong Province (hot summer/warm winter): public 2007
- Guangxi Province (hot summer/warm winter, hot summer/cold winter): residential 2013, public 2013
- Hainan Province (hot summer/warm winter): residential 2005
- Shanghai (hot summer, cold winter): residential 2011, public 2012
- Hubei Province (hot summer/cold winter): residential 2009

As of December 2015, five provinces or municipalities in hot-summer regions, and one in a temperate zone, recommend using cool surface materials their public and/or residential building design standards. Four local standards have added cool surface recommendations since the US-China Cool Roof Working Group first met in October 2010.

- Henan Province (hot summer/cold winter, cold): residential 2012, public 2006
- An'hui Province (hot summer/cold winter): residential 2010
- Zhejiang Province (hot summer/cold winter): residential 2015, public 2007
- Guizhou Province (hot summer/cold winter, hot summer/warm winter, temperate): residential 2008
- Jiangxi Province (hot summer/cold winter): residential 2014
- Yunnan Province (temperate): residential 2011

We also note that historically, the Chinese waterproofing industry has not participated in development of building energy efficiency standards. In spring 2016, Huasheng SHANG of the Chinese National Building Waterproofing Association stated that waterproofing experts would now engage with MOHURD in development of these standards.

In 2015, several Chinese waterproofing companies have started formulating high reflectance PVC waterproofing products as the results of the inclusion of heat island points in the 2014 Chinese national standard "Assessment standard for green building" (GB/T 50378-2014).

### Workshops

- US-China Cool Roof Working Group, October 2010, Shenzhen
- International Cool Roof Training Workshop, February 2011, Berkeley
- US-China Cool Roof Working Group, May 2011, Shenzhen
- Cool Roof Workshop for Chinese National Building Waterproofing Association, May 2011, Beijing
- International Workshop on Advances in Cool Roof Research, July 2011, Berkeley

- Cool Roof Workshop for Chinese National Building Waterproofing Association, January 2013, Berkeley
- Solar Reflective Materials Industrial Standard Workshop, July 2013, Xiamen
- International Cool Roof Workshop, July 2015, Berkeley
- Xiamen Cool Surface Workshop, December 2015, Xiamen

### List of Publications

- Gao Y, Xu J, Yang S, Tang X, Zhou Q, Ge J, Xu T, Levinson R. 2014. Cool roofs in China: Policy review, building simulations, and proof-of-concept experiments. Energy Policy 74, 190-214. This landmark paper demonstrates the energy, cost, and emission saving benefits of cool roofs in China
- Cao M, Rosado P, Lin Z, Levinson R, Millstein D. 2015. Cool roofs in Guangzhou, China: outdoor air temperature reductions during heat waves and typical summer conditions. Environ. Sci. Technol. 49 (24), 14672–14679. This landmark paper shows how widespread cool roofs can help mitigate urban heat islanda in China, especially during heat waves
- Patent Applications:
- US 2014/0090578 A1 "Method of making superhydrophobic/ superoleophilic paints, epoxies and composites", Simpson, Hunter, Filing date: Feb 1, 2013, Publication date: Apr 3, 2014.
- US 2014/0155522 A1 "Durable superhydrophobic coatings", John T Simpson, Georgios Polyzos, Daniel A. Schaeffer, Filing date: Mar 11, 2013, Publication date: June 5, 2014.
- US 2014/0094540 A1 "Superhydrophobic powder coatings", John T. Simpson, Filing date:Sep 28, 2012, Publication date: Apr 3, 2014.

## Collaboration

Dow Chemical supported some of early infrastructure development, including arranging the May 2011 workshop with the Chinese National Building Waterproofing Association in Beijing, and providing coating materials for a cool roof experiment in Chongqing. However, the vast majority of our collaboration with Dow Chemical took place within the cool roof technology development effort, which is documented in its own final summary report.

Nearly all activities described in the final program report were performed in collaboration with our Chinese colleagues. We had four primary partners (CU, GPABR, RISN, and IAP) and seven secondary partners (Shenzhen IBR, Xiamen IBR, Jiangsu IBR, Sichuan IBR, Shangxi IBR, Xijiang IBR, and China Building Material Test & Certification Group). Levinson (LBNL) traveled to China on CERC business six times, while GE (LBNL), XU (LBNL) and Millstein (LBNL) each did so once. GPABR and RISN each visited Berkeley three times.

Input from our Chinese partners was helpful in accurate characterization of Chinese construction practices and occupant behavior, which can differ substantially from those in the U.S. Our partners also performed all the field work in China, with guidance from LBNL.

Most impressive were the cool roof code development and natural exposure trial efforts led by RISN and GPABR. RISN and GPABR brought many other Chinese BRIs into the program, and found non-CERC funding to support Chinese participation in these activities.

## Conclusions

Collaboration between LBNL and its 11 Chinese partners over the past five years has substantially advanced the science and infrastructure of cool roofs in China. We determined through simulations that cool roofs conserve energy, save money, and reduce emissions in all hot-summer Chinese climates, and measured cool roof savings in real buildings in Chongqing and near Guangzhou. We found that the widespread adoption of cool roofs could significantly reduce summer afternoon air temperature, especially during heat waves, in the hot and populous city of Guangzhou. We conducted a year-long experiment in Chongqing comparing black, white, and garden roofs. We started natural exposure trials in nine Chinese cities that will track the changes over time of the albedo (solar reflectance) of cool roofing products, and will eventually be used to adapt to Chinese climates LBNL's lab aging practice for roof materials. We added to national Chinese standards a credit for the use of cool roofs on residential buildings in hot summer/warm winter climates, and credits for the use of cool roof and cool wall coatings on all buildings in hot summer climates. Additionally, we developed and tested several coating formulations. According to the LBNL aging testing that is equivalent to 3 years of natural exposure (ASTM D7897) the ORNL SH coating demonstrated 3.3 and 4.9% reduction in the solar reflectance and the water contact angle, respectively. The initial values of the solar reflectance and water contact angle are 0.778 and 167˚, respectively. Eliminating the use of solvents and improving the dispersion of the particles is necessary in order to scale-up the coatings and make them viable for commercial applications.

# Advanced Lighting Controls in New and Existing Buildings

***Joint Project***

## U.S. Partners

- **Lawrence Berkeley National Laboratory**
- **Lutron Electronics Co., Inc.**

## China Partners

- **China Academy of Building Research**
- **Lutron Electronics Co., Inc.**

## Overview

Since their introduction decades ago, lighting controls have presented a dilemma with regards to energy savings. These systems offer the potential for substantial energy savings, but it is extremely difficult to quantify exactly how much savings a particular lighting controls technology or strategy may yield. Even after a lighting controls system is installed, it can still be difficult to quantify savings as it can be extremely dependent on occupancy patterns, user preferences, seasonal variations, and/or weather patterns, which themselves can be extremely variable. The net result is that investments in energy efficiency lighting are often redirected to more predictable – but perhaps less cost effective – technologies, such as higher efficacy light sources or lamps and ballast retrofits. Essentially decision makers often take the guaranteed and verifiable 20% savings over the potentially more difficult to verify 30%-50% savings.

This project gets at the heart of the matter relative to promoting advanced lighting control systems' adoption in the marketplace.

- First, give the user confidence that the estimated savings are achievable and accurately reported through the lighting control system.
- Second, more effectively commission these systems with a separate control strategy, overcoming the lack of explicit operational information. Similarly, utility EE programs must be able to properly attribute savings to the various control strategies as required by their regulators for M&V purposes.
- Third, build a strong foundation to moving towards 'outcome-based' energy codes whereby compliance is accurately self-reported by the lighting control systems and we can eliminate the need for expensive and intrusive external EM&V.

Increasingly sophisticated and "connected" lighting controls systems are starting to address this dilemma. A new generation of lighting controls is emerging that can estimate energy use and savings down to the individual luminaire level and estimate how much energy the system is saving from each control strategy (e.g., daylight harvesting, occupancy sensing, etc.). This access to informative data has been missing until recently and may have value in a variety of ways:

- Building managers can see exactly how much energy their systems are using and explore strategies for achieving deeper savings.
- Lighting controls manufacturers can better market their systems by showing potential customers verified savings reports for applications from similar customers.
- Energy-efficiency program designers may be more interested in promoting advanced lighting controls systems investments when the risks associated with variable and/or unverified savings are mitigated.
- Regulators with an interest in reducing overall building energy use (rather than simply reducing lighting power density) can use this data for compliance verification for next generation "outcome-based" codes.

## Research Objectives

The main research objective was to determine how accurately lighting control systems self-report energy usage and savings once a given lighting control system is installed and commissioned with respect to the lighting loads it manages. To meet this objective, the research team developed a test protocol to evaluate measured versus reported lighting energy use over a variety of settings and environmental conditions. This test protocol was initially used to evaluate the

Lutron Quantum system operation, and it can be further refined to evaluate other lighting controls systems more generally.

A secondary research objective was to evaluate how changes in energy savings corresponded to changes in lighting quality metrics. Specifically, the research team looked at which controls setting and environmental conditions generated energy savings and improved glare metrics and which conditions generated savings at the expense of lighting quality. This second research objective was added during testing, as we were able to extend and expand our testing period beyond what we had planned.

Other research objectives include identifying the energy savings associated with individual lighting system control strategies and to convincingly demonstrate lighting controls systems' added value and cost-effectiveness for effecting deep reductions in lighting energy and demand in existing US buildings and new construction in China.

## Major Accomplishments

This project directly addressed the lack of existing standards or test procedures that describe how lighting controls systems should measure, estimate, record or report energy use or attribute energy savings. It accomplished this by measuring lighting system performance over a broad range of conditions and controls settings, and then comparing reported luminaire-level energy use to measured energy use. While the test presents the reported-versus-measured results for a specific lighting controls system, the methodologies developed can be applied more broadly to lighting controls systems generally. Ultimately these methods may lead to test procedures and codes for lighting controls systems that ensure accurate and uniform energy use reporting.

## Summary of Research Activities

### Year 2015

**SUMMARY OF TASKS**

Figure 1: Diagram (above) & photo of DOE's FLEXLAB facility at LBNL. This experiment utilized one of the two rotational test cells in this photo's foreground.

*Technology Evaluation (FLEXLAB)*

FLEXLAB testing makes it possible to commission the installed lighting controls in stages – something that allows us to isolate the individual control strategies' (daylighting, light level tuning, occupant-responsive lighting) energy saving impacts rather than just measuring the effect of all the strategies together. [NOTE: this is extremely difficult to achieve in the field because it inflicts too much hardship on the building occupants.] In a more permissive demonstration environment, it is also possible to explore cost vs. capabilities tradeoffs thus increasing the generalizability of the final project outcomes. This project gives the Team the opportunity to execute just such an improved experimental design.

In addition, the lighting controls solutions tested in FLEXLAB were 'driven' by live occupancy data from the CABR building in Beijing. By coordinating the testing between the two sites, the results using real world data will provide outcomes that can be better generalized to a broad swath of commercial floorspace in both China and U.S.

The following is an overview of the work we accomplished in this task:

- Finalized lighting controls systems' specification we evaluated.
- Developed experimental plan appropriate to evaluating the specified lighting controls system performance in the FLEXLAB testing facility
- Installed lighting controls system in the FLEXLAB testing facility
- Tested and evaluated lighting controls systems in FLEXLAB according to the experimental plan.
- In each scenario tested, we compared FLEXLAB measured energy use, savings, etc., to that reported by Lutron system
- Identified scenarios that generated discrepancies in reported results
- We looked to establish corrections for Lutron system, and if not possible, we identified scenarios where Lutron system results were likely to have higher uncertainty levels
- Prepared report detailing laboratory lighting controls system testing results (sample plots shown below)

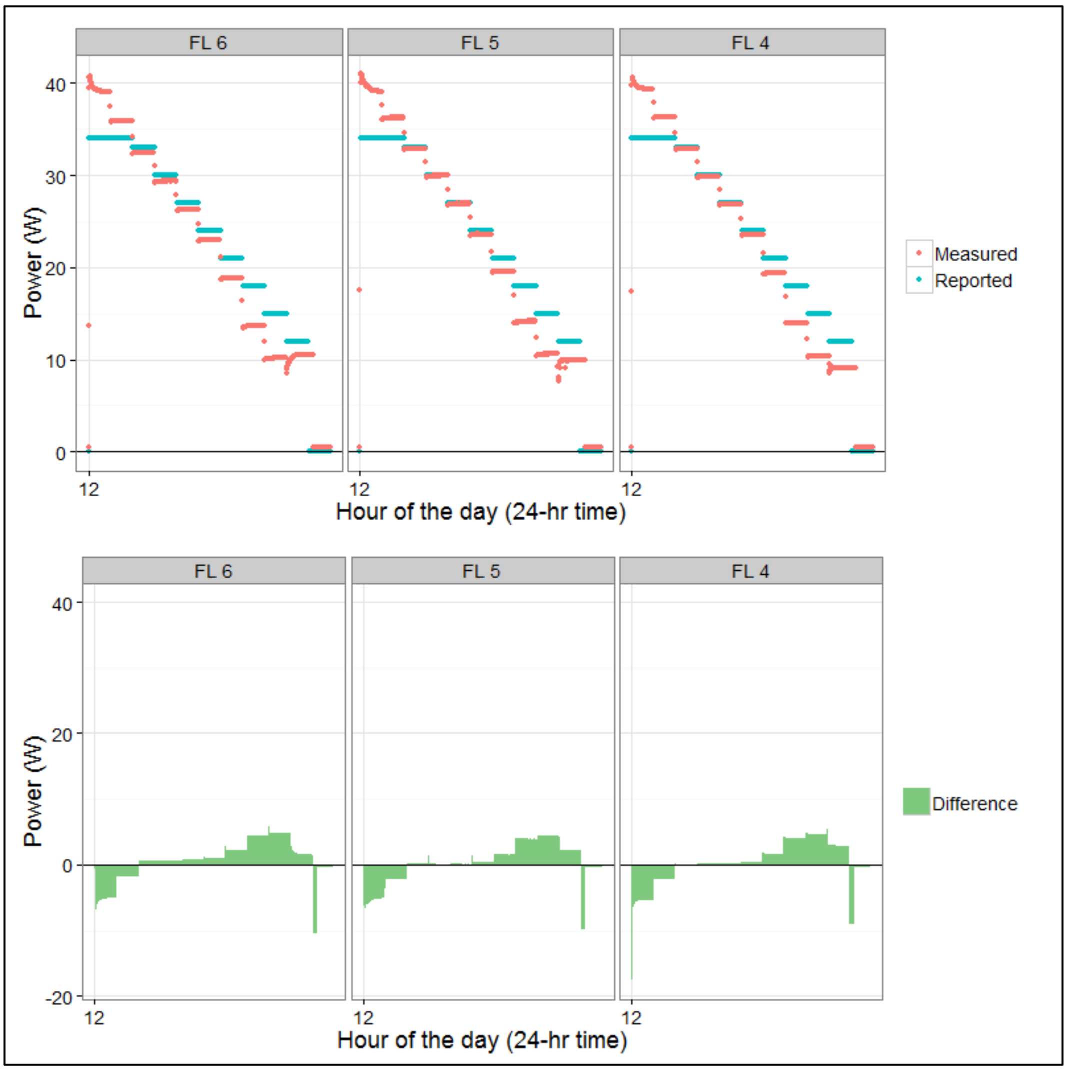



**Figure 2: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for fluorescent luminaires during sample step dimming period**

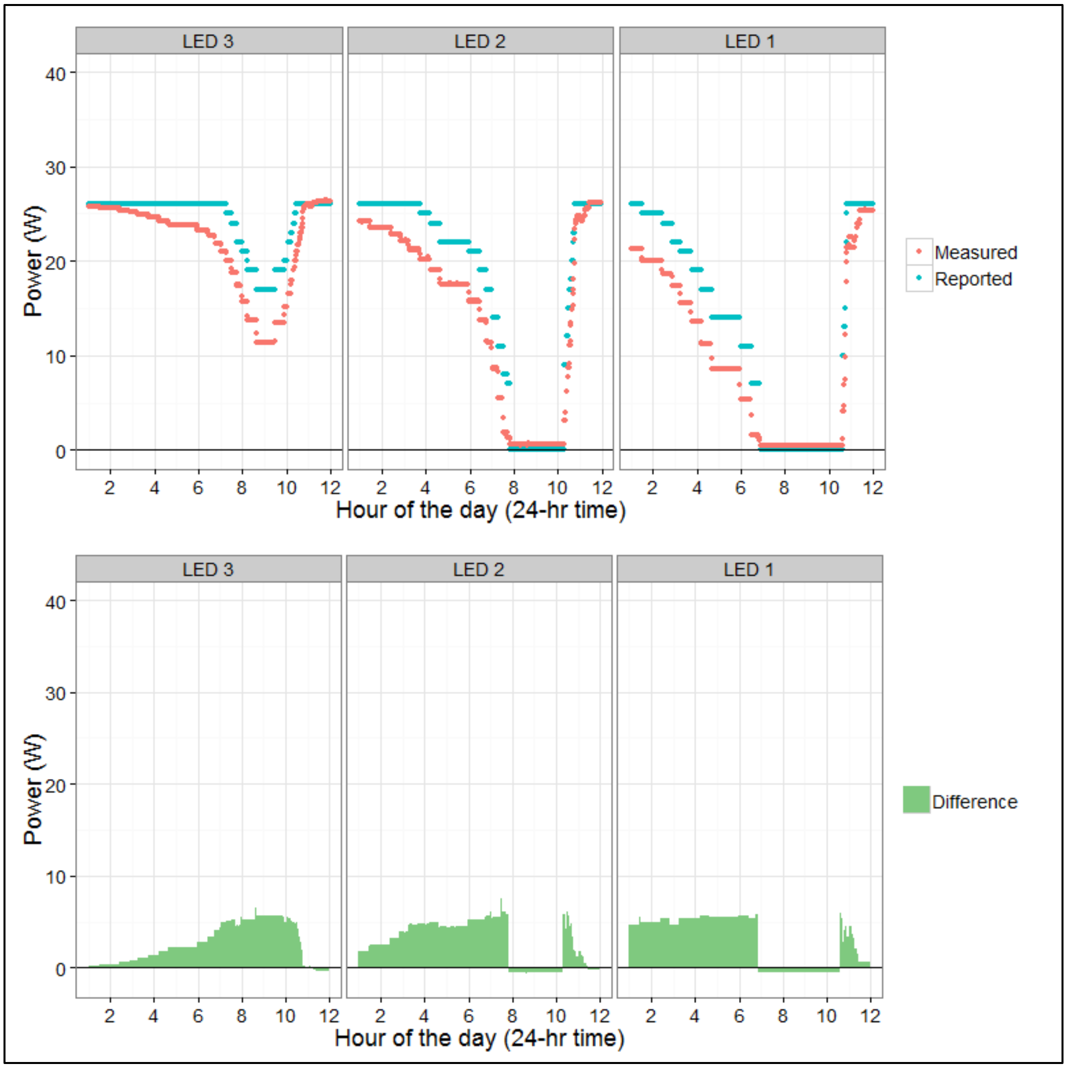



**Figure 3: Upper plot shows measured & reported power values, lower plot shows difference between reported & measured power for LED luminaires during sample daylight harvesting period**

**Table 1: Average power as reported by FLEXLAB, under all control strategies for all luminaires**

| Luminaire | Baseline (W) | Daylight Harvesting (W) | Savings | Occupancy Only (W) | Savings | Occupancy plus Daylight Harvesting (W) | Savings |
|---|---|---|---|---|---|---|---|
| FL 6 | 39.1 | 33.6 | 14% | 20.2 | 48% | 18.6 | 52% |
| FL 5 | 37.7 | 23.5 | 38% | 20.3 | 46% | 9.4 | 75% |
| FL 4 | 38.4 | 17.9 | 53% | 20.4 | 47% | 6.3 | 84% |
| All FL | 115.2 | 74.9 | 35% | 60.8 | 47% | 34.3 | 70% |
| | | | | | | | |
| LED 3 | 26.5 | 21.9 | 17% | 13.8 | 48% | 12.0 | 55% |
| LED 2 | 26.4 | 15.6 | 41% | 14.0 | 47% | 5.9 | 78% |
| LED 1 | 25.7 | 11.1 | 57% | 13.8 | 46% | 4.0 | 84% |
| ALL LED | 78.7 | 48.7 | 38% | 41.6 | 47% | 21.9 | 72% |

Table 2: Average power as reported by Lutron system, under all control strategies for all luminaires

| Luminaire | Baseline (W) | Daylight Harvesting (W) | Savings | Occupancy Only (W) | Savings | Occupancy plus Daylight Harvesting (W) | Savings |
|---|---|---|---|---|---|---|---|
| FL 6 | 34 | 32.6 | 4% | 17.3 | 49% | 18.0 | 47% |
| FL 5 | 34 | 24.4 | 28% | 17.2 | 49% | 8.9 | 74% |
| FL 4 | 34 | 20.5 | 40% | 17.2 | 49% | 6.0 | 82% |
| All FL | 102 | 77.5 | 24% | 51.7 | 49% | 32.9 | 68% |
| | | | | | | | |
| LED 3 | 26 | 24.9 | 4% | 13.2 | 49% | 13.8 | 47% |
| LED 2 | 26 | 19.4 | 25% | 13.2 | 49% | 6.8 | 74% |
| LED 1 | 26 | 15.5 | 40% | 13.2 | 49% | 4.6 | 82% |
| ALL LED | 78 | 59.8 | 23% | 39.6 | 49% | 25.2 | 68% |

*Develop controls system reporting algorithms*

- Vetted algorithms with industry stakeholders
- Revised algorithms to reflect appropriate feedback
- Provided technology transfer to industry stakeholders

*Develop proposed advanced lighting controls system standard for reporting*

- Identify and contact key stakeholders in China working with CABR
- Identify and contact key U.S. stakeholders
- Establish advanced lighting controls system standard reporting template for dissemination
- Vet template with U.S. code stakeholders
- Distribute template to appropriate standards organizations

**MAJOR FINDINGS AND OUTCOMES**

- Experimental plan for evaluating lighting controls system in FLEXLAB
- Report with results and recommendations from FLEXLAB evaluation
- Installation of lighting controls systems in FLEXLAB
- Development of final advanced lighting controls system reporting algorithm

## Major Outcomes and Achievements

We measured and confirmed, Lutron controls system's "notional power metering" for a variety of daylight and occupancy conditions. [NOTE: All lighting control systems estimate energy consumption at either the aggregated node or device level through the use of standard lookup tables. This approach inherently limits reporting accuracy in particular with dynamic controls.] This approach relates directly to two project objectives:

- Calibration/Verification of Notional Power Metering: Comparing CABR field site reports generated by the Lutron controls systems to detailed measurements taken within the FLEXLAB will allow us to calibrate and correct (as needed) the reports generated by the Lutron controls systems. This will provide us with an improved understanding of the lighting system performance and energy use when viewing Lutron controls system reports.
- Establishing General Protocols for Notional Power Metering: More generally, we explored and documented the opportunities and limitations of notional power metering and provided recommendations for OPEN industry standard approaches to utilizing these techniques in order to improve lighting controls system energy reporting accuracy.

For the first time, we produced disaggregated energy savings at the device level with discrete attribution by control strategy (i.e., the savings associated separately with occupancy sensing, daylighting, etc.). All research products aimed at producing open and widely promulgated information, NOT information proprietary to Lutron.

- Leveraged research results with PG&E and NEEP which is working with us to calibrate their advanced lighting controls calculator using our actual FLEXLAB data to ensure its accuracy before rolling out to support their advanced lighting programs.

- The project directly builds the foundation to move to ‘outcome-based’ energy codes and standards and answers the utilities’ desire to know how to attribute energy savings per disaggregated lighting control strategy for program design use and for reporting to their regulators.
- The project gets at serious system commissioning questions because most lighting control systems estimate end-use device operation (using static lookup tables) both in terms of energy but also light levels—this project addressed that question head-on to develop new algorithms based on dynamic system operation per control strategy to more accurately report these values.

## Collaboration

Lutron Electronics Co., Inc. has provided significant cost-share both in terms of hardware/software (complete latest generation Quantum lighting controls system, sensor package, Finelite LED & fluorescent fixtures), and with on-site and remote technical support. Continuing engagement by Lutron’s Lead Scientist, Dr. Nachtrieb, provided overall guidance and coordination with Lutron’s resources in U.S. and China, and was an extremely valuable resource to the research team.

We also learned that when dealing with private industry as part of the research project, it is necessary to allow significant lead times to obtain equipment and shared resources because, as expected, they are set up to manage a sales/business process rather than a research process. This means that donated or purchased equipment needs to go through their normal sales channels with appropriate approvals up and down their management chain.

Lutron is looking to collaborate in the future and especially support industry-wide standards setting initiatives as an outgrowth of the research project. They have been a very forthright and supportive partner.

## Conclusions

While LBNL performed tests on a single lighting system, the testing protocol developed may have wider applicability. We can envision a test procedure for evaluating this broader set of lighting systems that would be similar to the step-dimming test we performed in the FLEXLAB. This test could be done as a power-only “bench top” test that simply compares the measured luminaire power to the lighting control system reported power through a range of different dimming settings. The purpose of this test would be to document errors in energy use, whether they were power-level related (e.g. power reported as 10W but measured as 12W) or time-period related (e.g., power reported to drop after 1 hour but measured to drop after 1 hour, 5 minutes). This test could be used both for lighting control systems that directly measure luminaire power as well as those that report power based on control settings and power look-up tables.

The results from the additional test described above would provide information about lighting controls system-reporting accuracy in general (e.g., are the results found in this report typical of lighting controls system self-reporting or atypical?). This test procedure development may serve as a valuable device for evaluating lighting control system reporting performance, perhaps ultimately resulting in a methodology for certifying self-reporting system accuracy. Codes, standards and/or utility programs could rely on these test procedures to encourage the use of lighting controls systems that are appropriately accurate at self-reporting. This enhanced methodology has significant cost savings and value across industry stakeholder groups in verifying accurately lighting system performance.

One of the key lessons arising from this research that is typically represented as a market gap, is that a significant number of construction projects involving lighting controls system installations lack either the budget, scope description, time frame or singularly accountable professional to adequately obtain and commission accurate luminaire lamp/ballast or LED/driver performance look up tables into a specific manufacturer’s control system. Additionally, its important to recognize that frequently, a single project involves integrating a large number of different luminaires from different manufacturers, suppliers, distributors, and wholesale representatives, and that projects lack fully-funded commissioning agents and a single information channel sourcing accurate look up tables. This is not necessarily the failing of the resident lighting controls system reporting, but rather an artifact of the information interjected in it in an inherently ‘flawed’ construction process. With that said, our research does indicate a modicum of reporting errors associated with varying light source/driver/luminaire combinations. The seriousness of these errors is highly dependent on the extent of employed control strategies and obviously the veracity of the luminaire performance tables. More research in this area would establish a firmer foundation for the full market impact related to this issue.

# Advance Ground Source Heat Pump Technology for Very Low Energy Buildings

***Joint Project***

## U.S. Partners

- Oak Ridge National Laboratory
- ClimateMaster

## China Partners

- Tongji University
- Tianjin University
- Chongqing University
- China Academy of Building Research

## Overview

GSHP is a proven technology that utilizes the clean and renewable geothermal energy, as well as the massive thermal storage capacity of the ground, to provide space conditioning and water heating for both residential and commercial buildings. It has higher energy efficiency than most conventional space conditioning and water heating systems. This project will help accelerate the adoption of GSHP technology to reduce fossil fuel consumptions and associated carbon emissions for space conditioning and water heating. It is estimated that 0.6 Quad Btu primary energy consumptions and 38 million tons of carbon emissions will be reduced each year if GSHP gets 10% market share in the US. In addition, this project will also help sustain the rapid growth of GSHP applications in China by improving quality standards and introducing the advanced GSHP equipment and engineering services provided by US vendors.

## Research Objectives

Reduce initial cost and further improve operational efficiency of ground source heat pump (GSHP) systems by developing low-cost and performance neutral ground heat exchangers (GHXs) and smart controls at component and system levels; accelerate adoption of GSHP technology in both China and the US by exchanging best practices in GSHP applications between the two countries.

## Major Accomplishments

This project identified and developed a few new technologies needed for the next-generation of GSHP applications, including new low-cost performance neural GHXs, a smart pumping control, and a cost-effective virtual sensing based performance monitoring and fault detection system. Combined with the advanced ground source integrated heat pump (GS-IHP) previously developed by ORNL and ClimateMaster, the next-generation GSHP system will be more cost effective and capable of satisfying the space condition and water heating demands in buildings. It will be more intelligent and able to optimize its operation based on thermal loads. Its performance will be more accountable and visible to its owners or investors. The flexible research facility for the distributed GSHP (DGSHP) systems built for this project provides a first-of-a-kind facility capable of supporting development and verification of various emerging technologies for GSHP applications in a low-risk and realistic real-building environment.

## Summary of Research Activities

### Year 2011

**OBJECTIVE**

- Develop a US-China joint research plan, compare the state-of-the-art of GSHP applications in both countries, and establish collaboration with Chinese counterparts and GSHP industry

**SUMMARY OF TASKS**

- Research teams in the two countries developed a 10-point joint work plan for advancing GSHP technology

- Research teams reviewed the applications, performance, market development, and related policies of GSHP in both countries
- ORNL conducted a survey of the geological information available in the US to the public that is useful for the design and installation of GHXs
- ORNL started evaluating eight new GHXs in collaboration with Oklahoma Gas and Electric, the International Ground Source Heat Pump Association, ClimateMaster (the industry partner of this project), and other stakeholders in the US GSHP industry

**MAJOR FINDINGS AND OUTCOMES**

- A 10-point US-China joint work plan for advancing the GSHP technology
- A report reviewing the state-of-the-art of GSHP applications in US and China
- A report summarizing the available geological information in the US useful for the design and installation of GHXs

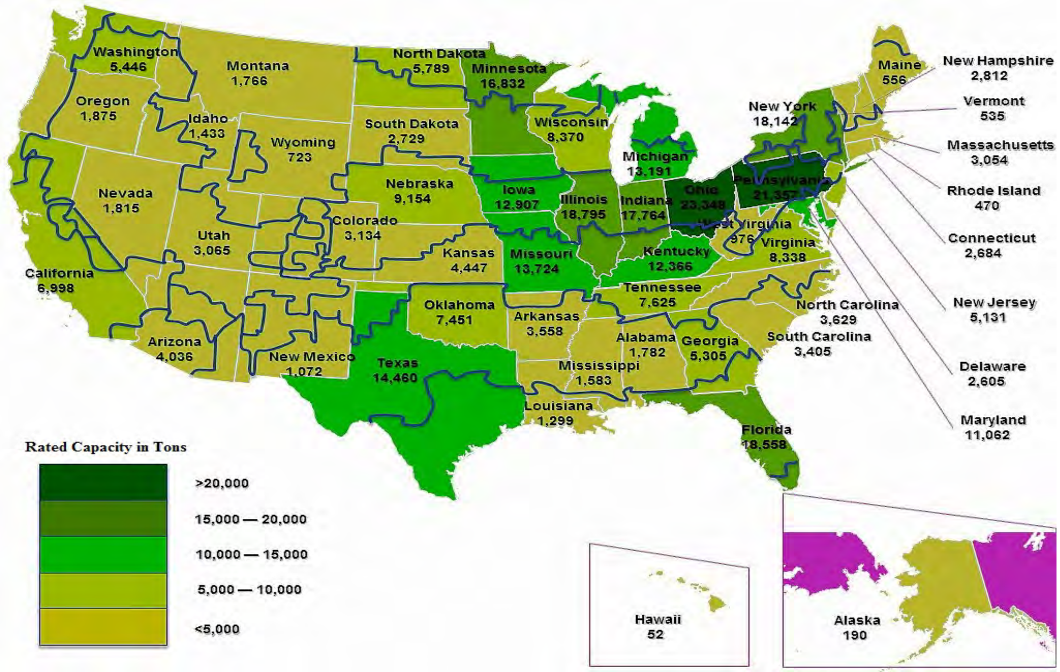



**Figure 1: Distribution of GSHP unit shipments in the United States in 2009 (Data source: EIA)**

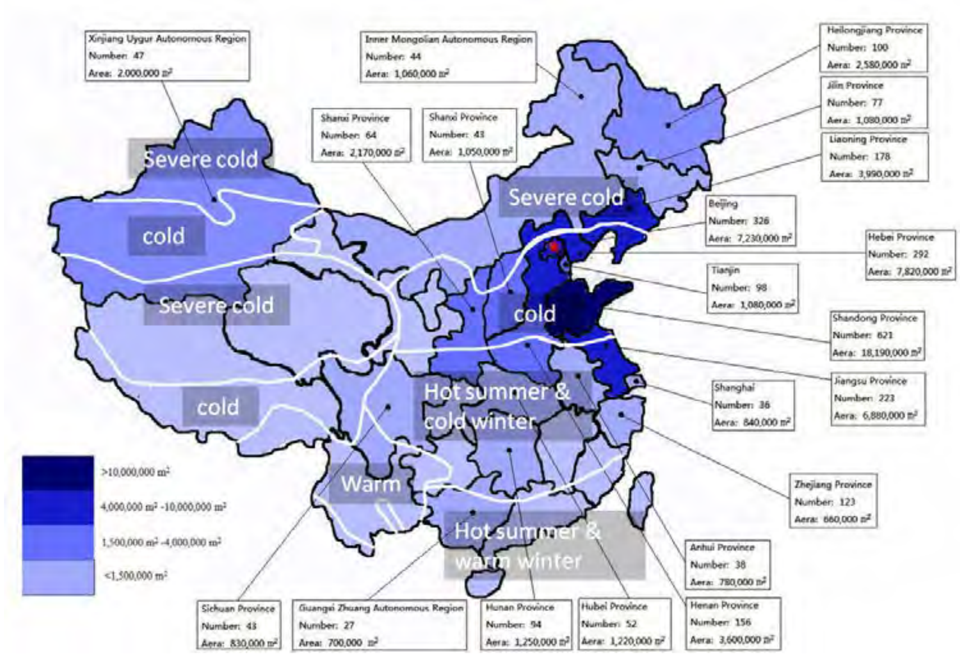



**Figure 2: Distribution of GSHP applications in China (Data source: CGSB)**

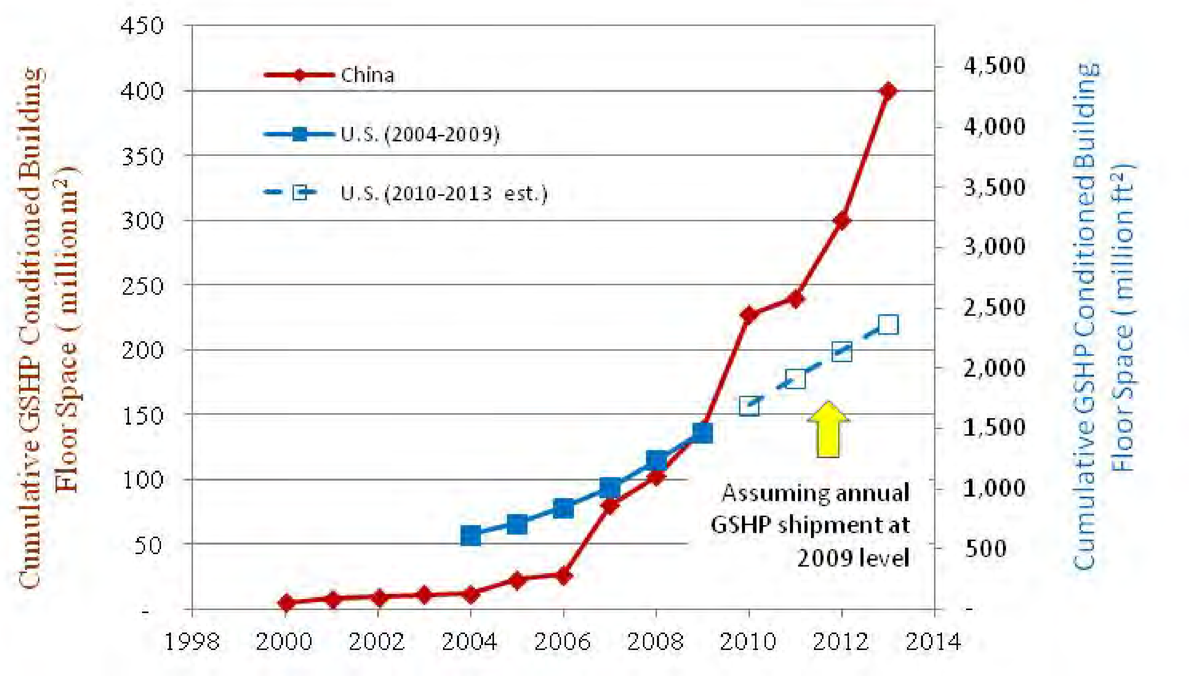



Figure 3: Cumulative GSHP conditioned floor space in the U.S. and China (Liu et al. 2015)

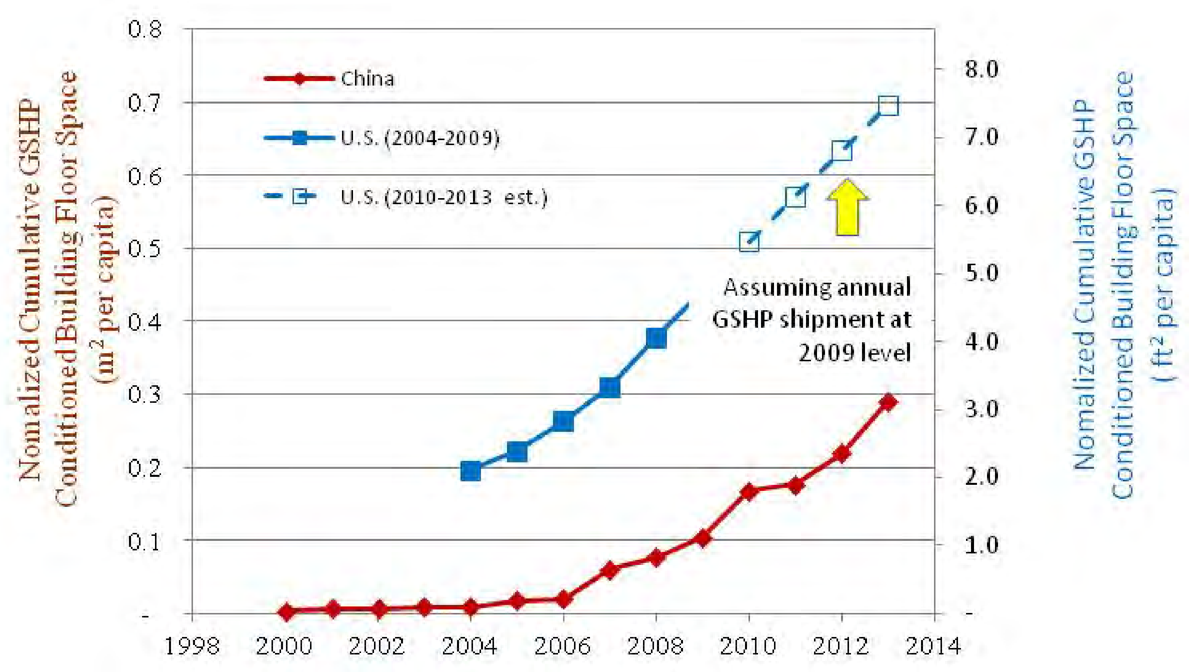



Figure 4: Cumulative GSHP conditioned floor space in the U.S. and China (Liu et al. 2015) (Normalized)

## Year 2012

### OBJECTIVE

- Identify technologies that have potential to reduce the cost and improve the performance of GSHP systems through a systematic evaluation of various GSHP technologies developed in China and the United States

### SUMMARY OF TASKS

- ORNL and Chinese researchers compared GSHP applications in China and the US based on the status review conducted by each country
- ORNL developed a protocol for evaluating performance of GSHP systems in both countries, including data collection, key performance metrics, baseline systems, calculation procedures, and building energy simulation tools

- ORNL collected and analyzed performance data following the protocol from existing GSHP systems, including 10 identical Habitat Humanity Homes, which use new or conventional GHXs, the GSHP system installed at the headquarter building of American Society of Heating, Refrigeration and Air-condition Engineers (ASHRAE), and six other GSHP projects in the US
- Chinese researchers conducted case studies for more than 30 GSHP systems in China

**MAJOR FINDINGS AND OUTCOMES**

- The comparative study on GSHP applications in China and the US found that (1) GSHP installations in China have grown from zero to 400 million m2 (4.3 billion ft2) of building floor space in the last decade, which has already surpassed that in the United States (roughly 199 million m2, or 2.14 billion ft2); (2) the annual growth rate of GSHP applications in China (46%) is much higher than that in the US (11%) due to the massive construction in China, shortage of energy supplies and severe air pollution, and the strong governmental support; (3) most GSHP systems in the US are in a distributed configuration (i.e., DGSHP systems), but the less energy efficient central GSHP systems are commonly used in China; (4) high initial cost is the primary barrier preventing wider adoption of GSHP in the US, but the lack of standards governing quality of equipment, design, installation, and operation of GSHP is the main barrier in China, and (5) further collaboration in several areas will benefit both countries, including quality standards, professional trainings, heat pump equipment, system integration and control, as well as the policy and incentives for promoting GSHP applications.
- The field evaluation identified new GHXs that require 14-30% less drilling than the conventional GHX while delivering the same performance.
- Invented a new method and developed corresponding analysis tool for cost effectively monitoring performance and detecting faults of DGSHP systems (Invention Disclosure #: 201403380, DOE S-number: S-138,004)

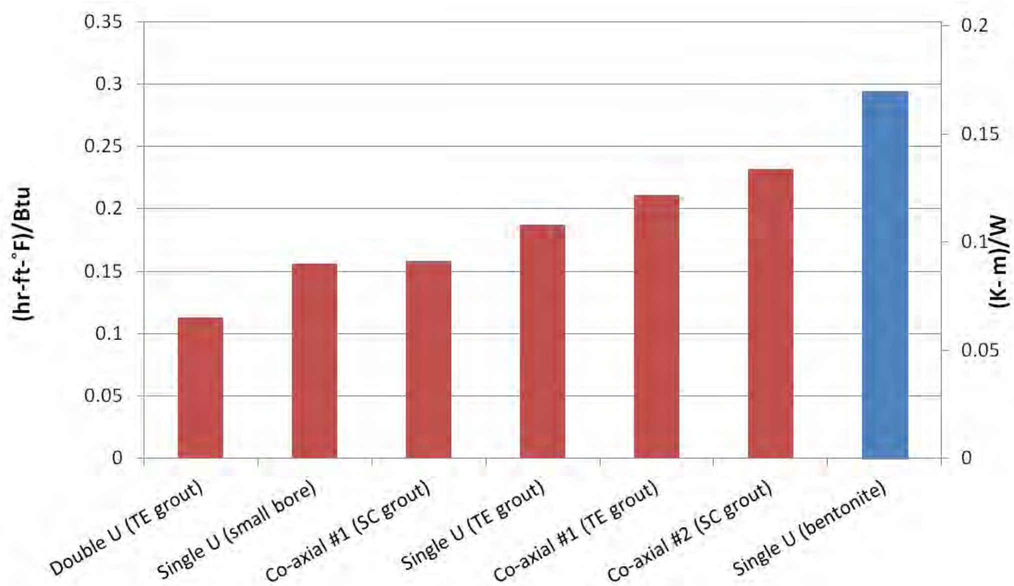



Figure 5: Borehole thermal resistance of various GHXs (Liu et al. 2013)

## Year 2013

**OBJECTIVE**

- Further advance DGSHP technology by improving both component and system level controls

**SUMMARY OF TASKS**

- ORNL and Oklahoma State University jointly analyzed performance of two HAVC systems installed at the ASHRAE HQ—an air-source variable refrigerant flow (VRF) system serving 1st floor and a DGSHP system serving the almost identical 2nd floor.
- ClimateMaster set up an experimental apparatus to test various controls for the water heating operation of the Trilogy™ 40 Q-Mode™ series GS-IHP, which won the 2013 R&D 100 Award

- ORNL investigated new controls to further improve the water heating performance of the GS-IHP and to reduce the pumping power consumption of DGSHP systems
- ORNL preliminarily designed a flexible research platform for DGSHP systems to test new controls

**MAJOR FINDINGS AND OUTCOMES**

- Revealed the significantly different performance between the air-source VRF and DGSHP systems at the ASHRAE HQ building. The analysis indicates that the DGSHP system used 44% less energy than the VRF system for conditioning each unit of the building floor space. The difference is due to not only the more favorable ground temperature than the ambient air temperature, but also the wasted energy resulting from the self-conflicting simultaneous heating and cooling of the VRF system in a space with open floor plan. The results of this study were published in two technical papers at ASHRAE Journal in 2014.
- Two candidate controls for water heating of GS-IHP were identified: one is to reset tank temperature based on the historical or predicted hot water usage pattern, and the other is to dynamically coordinate between space cooling and water heating based on ground temperature. These controls were tested in 2015 at the flexible research facility at ORNL.

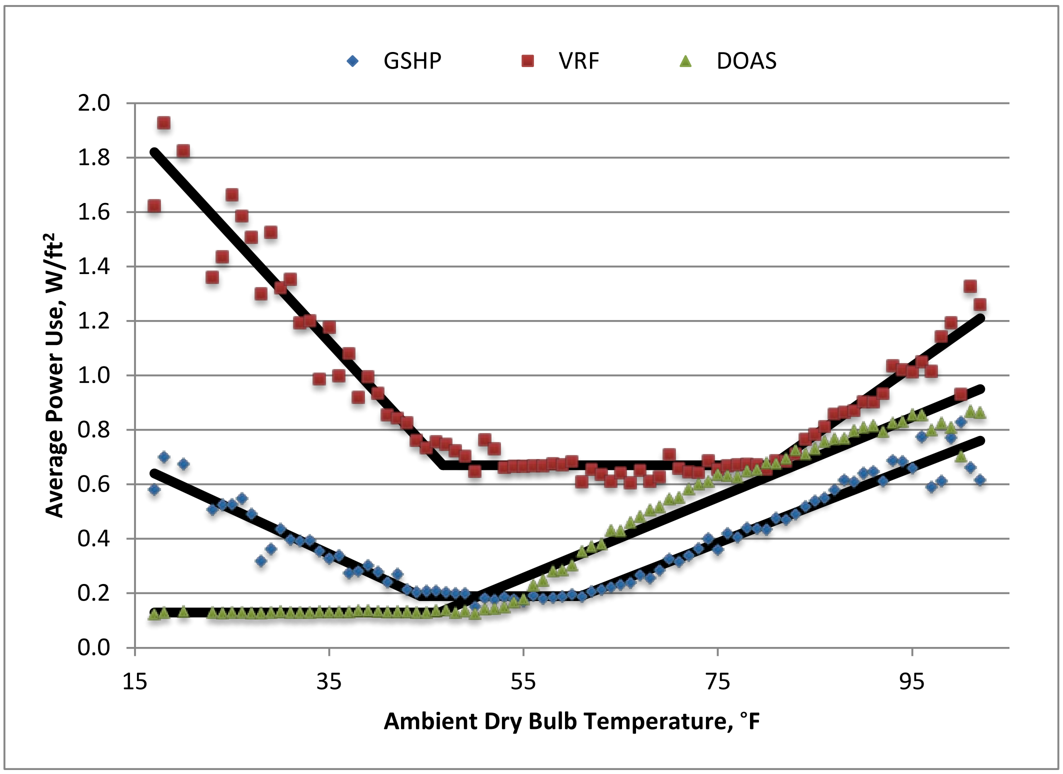



Figure 6: Normalized power consumption of various HVAC systems in the ASHRAE HQ building (Southard et al. 2014)

## Year 2014

**OBJECTIVE**

- Further advance DGSHP technology by improving both component and system level controls

**SUMMARY OF TASKS**

- ORNL and ClimateMaster revised the initial design of the flexible research facility for DGSHP systems to make it fit in the available budget and to comply with the environmental constraints at ORNL
- ORNL identified the cause for the excessive pumping commonly observed in DGSHP systems through analyzing numerous case studies of existing GSHP systems in both China and the US, and proposed a new flow-demand-based pumping control
- ClimateMaster conducted lab tests to characterize performance of existing and new water heating controls for the GS-IHP; and ORNL analyzed the test results and provided recommendations for refining the controls
- ClimateMaster and ORNL introduced distributed GSHP systems to the six candidates of CERC-BEE demonstration projects and provided guidance on system design and performance analysis

- ClimateMaster provided GSHP units and technical assistance to help Chinese Academy of Building Research (CABR) implement a small DGSHP system in its Very-Low-Energy-Building (VLEB)

**MAJOR FINDINGS AND OUTCOMES**

- An innovative flow-demand-based pumping control is invented to minimize the pumping power while providing sufficient water flow to each GSHP unit (Invention Disclosure #: 201403380, DOE S-number: S-138,004)
- Published the energy analysis results of the ASHRAE HQ building at the ASHRAE Journal and presented the field evaluation results of the new GHXs at the 11th IEA heat pump center conference
- Demonstrated the U.S. style DGSHP system at CABR's VLEB

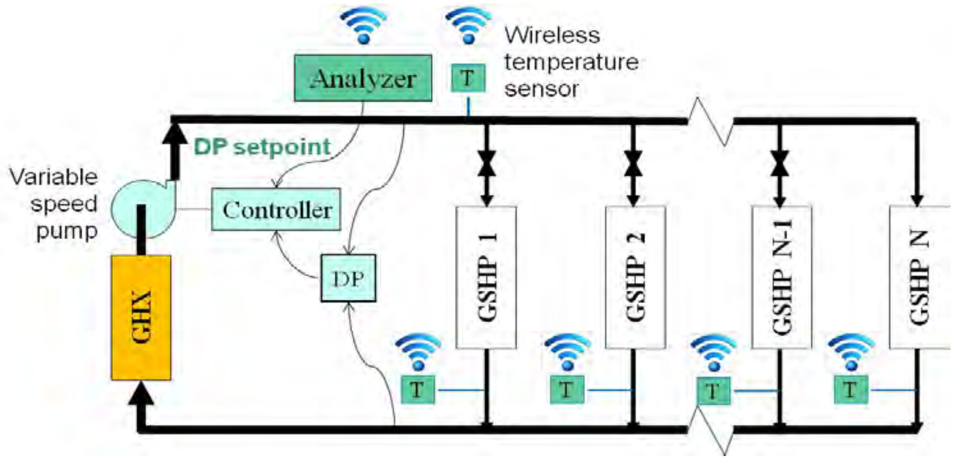



Figure 7: Diagram of a flow-demand-based pumping control for DGSHP systems (patent pending)

## Year 2015

**OBJECTIVE**

- Further advance DGSHP technology by improving both component and system level controls

**SUMMARY OF TASKS**

- ORNL built a first-of-a-kind research facility for DGSHP systems and implemented the proposed controls for the water heating operation of GS-IHP and the variable speed pump used in DGSHP systems
- ORNL conducted a series of tests at the research facility to evaluate the performance of the proposed controls at various operating conditions
- ORNL and the University of Alabama jointly conducted a simulation-based study to compare the performance of two conventional pressure-based pumping controls and the newly invented flow-demand-based pumping control
- ORNL provided guidance to Chinese collaborators on data collection and performance evaluation for GSHP systems, and reviewed the case study for CABR's VLEB

**MAJOR FINDINGS AND OUTCOMES**

- A first-of-a-kind research facility for DGSHP system is built and aggressively instrumented. It is comprised of (1) a ground source emulator, which can mimic the supply temperatures of various ground sources (e.g., groundwater, surface water, and ground loop); (2) a 12-ton DGSHP system with two 2-ton two-stage GSHP units and two 5-ton GS-IHP units; (3) a hydronic piping system with two pumping configurations; and (4) a data acquisition and visualization system to collect and visualize data from more than 100 sensors and meters.
- A new control for water heating operation of the GS-IHP, which uses additional inputs (e.g., historical hot water usage patterns, temperatures at various levels within the hot water tank, ground source temperature, etc.) to reduce the summer peak electricity demand by up to 50% without sacrificing space cooling and water heating performance
- A new flow-demand-based control that can reduce pumping energy of DGSHP systems by more than 20% while maintaining appropriate flow rate in each heat pump (patent pending)

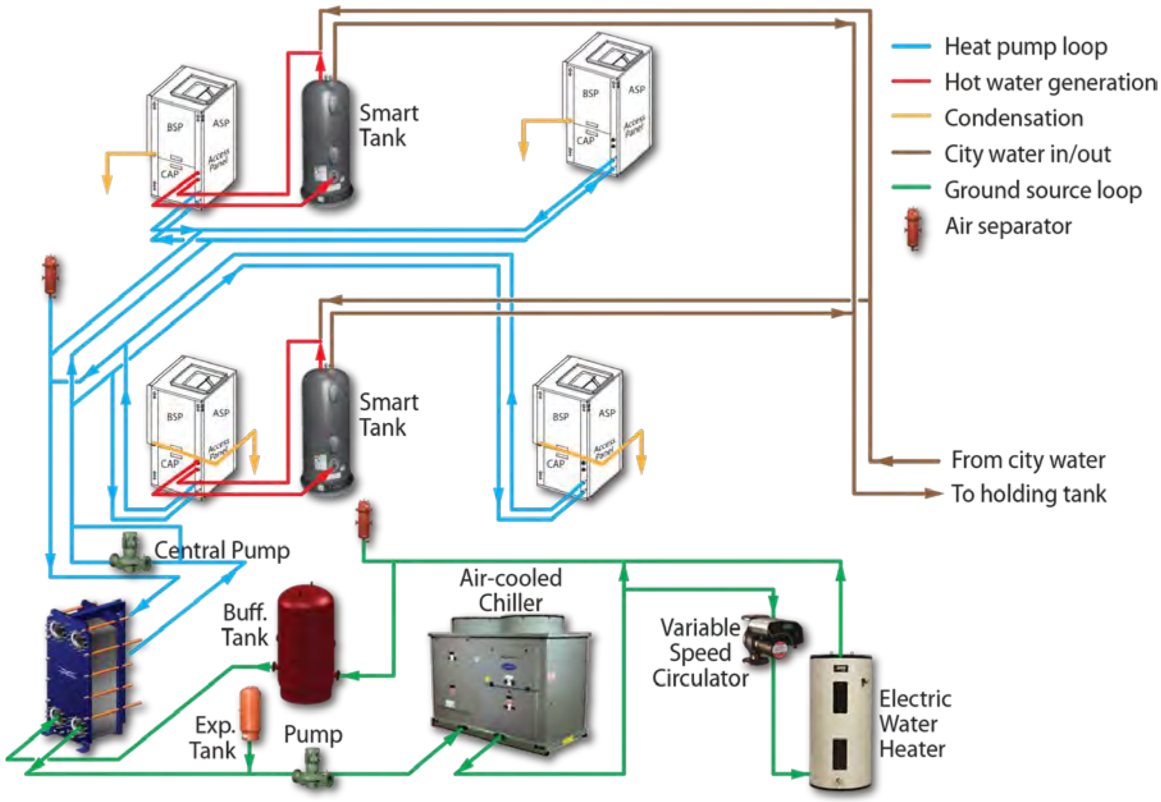



Figure 8: Schematic of the flexible research facility for DGSHP systems

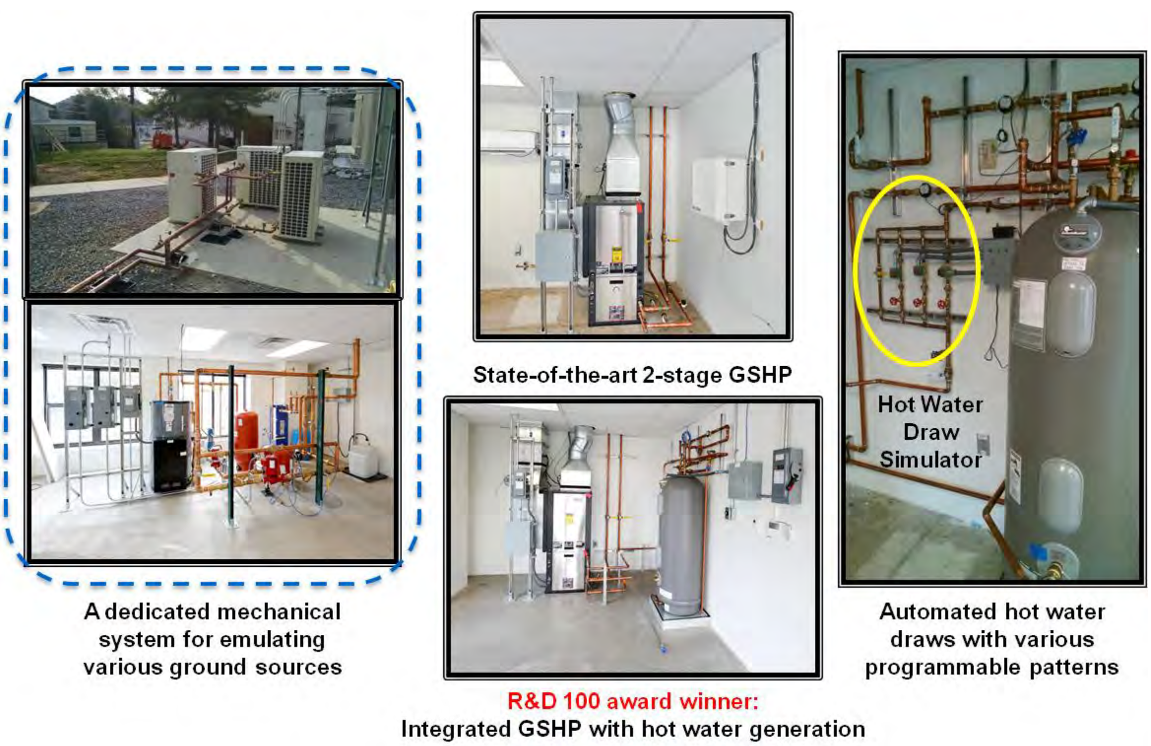



Figure 9: Major equipment of the flexible research facility for DGSHP systems

## Major Outcomes and Achievements

- Identified new GHXs that require 14-30% less drilling compared with conventional GHX while retaining same performance
- Designed and built a first-of-a-kind research facility capable of supporting development and verification of various emerging technologies for GSHP applications in a low-risk and realistic real-building environment
- Characterized performance of various GSHP systems in both countries and identified areas to further improve system efficiency
- Invented a new flow-demand-based control, which has potential to reduce pumping energy of DGSHP systems by more than 20% (patent pending, Invention Disclosure #: 201403380, DOE S-number: S-138,004)
- Developed a new method and enabling tool to cost effectively monitoring performance and detecting faults of DGSHP systems (Invention Disclosure #: 201403381, DOE S-number: S-138,005)
- Demonstrated a U.S. style DGSHP system in the highly visible very-low-energy-building of Chinese Academy of Building Research
- Published 12 journal and conference papers

### Products Launched

- A first-of-a-kind research facility for DGSHP systems was fully commissioned in April, 2015
- A protocol and software tool for analyzing the performance of DGSHP systems was developed in 2013
- Additionally, ClimateMaster launched the Trilogy™ 40 Q-Mode™ series GS-IHP in 2014. A new co-axial GHX developed by GroenHolland B.V. was launched in the US in 2013 after the field evaluation by ORNL and other organizations in 2012.
- The smart pumping control for DGSHP systems developed in this project will be installed in existing commercial DGSHP systems to demonstrate the benefits. It is expected that ClimateMaster will launch the smart pumping control in 2017. The smart pumping control would be introduced in trade shows (e.g., ASHRAE Winter Meeting, IGSHPA, regional events, etc.) starting from 2017. Field demonstration of the smart pumping control could also be done in China (e.g., at the small DGSHP system in CABR's VLEB).

### Standards, Codes, and Policies Influenced

- National Certification Standard for Ground Source Heat Pump Personnel, developed by Geothermal Heat Pump Consortium in collaboration with ORNL and other organizations (published in 2013)

### Workshops

- A workshop to introduce Chinese GSHP technologies and applications was held in conjunction with the 2012 IGSHPA annual conference in Tulsa, OK
- A video conference was held in 2012 to introduce eQUEST software to Chinese collaborators
- A workshop in Wuhan, China in 2014 to introduce the DGSHP system to the six candidates of the CERC-BEE demonstrations

### List of Publications


- Liu, X., S. Lu, P. Hughes, and Z. Cai. 2015. A Comparative Study of the Status of GSHP Applications in the United States and China, Renewable and Sustainable Energy Reviews, Volume 48, August 2015, Pages 558-570.
- Niu, F., X. Liu, and Z. O'Neill. 2016. A Simulation-Based Study on Different Control Strategies for Variable Speed Pump in Distributed Ground Source Heat Pump Systems. In press. ASHRAE Transaction, 2016.
- Southard, L., X. Liu, and J. Spitler, 2014. Performance of the HVAC Systems at the ASHRAE Headquarters Building, Part 1: Measured Energy Usage. ASHRAE Journal, September, 2014
- Southard, L., X. Liu, and J. Spitler, 2014. Performance of the HVAC Systems at the ASHRAE Headquarters Building, Part 2. ASHRAE Journal, in press and will be published in December, 2014
- Liu, X., R. Beier, M. Anderson, and G. Ewbank, 2014. "Field test and evaluation of residential ground source heat pump systems using emerging ground coupling technologies", 2014 IEA Heat Pump conference, Montreal, Canada.
- Liu, X., M. Malhotra, A. Walburger, and B. Habibzadeh, 2014. "Case study of a heating only central GSHP system using a shallow aquifer for a warehouse", 2014 ASHRAE annual conference, Seattle, WA.

- Liu, X., M. Malhotra and H. Henderson, "Case study of a distributed GSHP system in a high School", Proceedings of the 2015 ASHRAE Annual Conference, Atlanta, GA, June 27-July 1, 2015.
- Liu, X., M. Malhotra and A. Walburger, "Case study for a ground source heat pump system using mine water as heat sink and source", Proceedings of the 2015 IEA ECES Greenstock Conference, Beijing, China, May. 19-21, 2015.
- Im, P. and X. Liu, "Evaluation of the ground source variable refrigerant flow (VRF) system performance for a university building in cold climate", Proceedings of the 24th IIR International Congress of Refrigeration (ICR2015), Yokohoma, Japan, August 16-22, 2015.
- Liu, X., M. Malhotra, P. Im and B. Habibzadeh, "Case studies for GSHP demonstration projects in the US", IEA HPC Newsletter, September 2015.
- Lu, S., Z. Cai, L. Zhang, and Y. Li. 2014. Evaluation of the performance of a centralized ground-water heat pump system in cold climate region. Front. Energy. 2014, 8 (3): 394-402.
- Lu, S., et al. "Optimization model analysis of centralized groundwater source heat pump system in heating season." Frontiers in Energy (2015): 1-19.


## Collaboration

US researchers worked closely with ClimateMaster, the US industrial partner, from the very beginning of this project. We kept good communication throughout the past five years. The research team shared each proposal and quarterly report with ClimateMaster and met regularly to discuss the progress. ClimateMaster provided inputs, technical support, and feedback to the proposals and progress reports, donated heat pump equipment needed for this study and the demonstration at CABR's VLEB in China, and conducted initial lab tests to evaluate new water heating controls. Representatives of ClimateMaster visited China multiple times to attend meetings/workshops organized by CERC-BEE and hosted visits of Chinese GSHP industry. The research team plans to collaborate with ClimateMaster to commercialize the smart pumping control developed in this project in both the US and China.

US researchers established a good communication and working relationship with the Chinese researchers during the first year of CERC-BEE through in-person meetings and regular tele-conferences. Researchers from both countries jointly developed a work plan for the first two years of the project. U.S. researchers shared with Chinese counterparts the best practice, tools, and case study reports for evaluating the performance of GSHP systems in the US. Chinese researchers introduced their experience in large scale GSHP applications that use conventional or uncommon ground sources (e.g., filtered raw sewage water and building foundation piles). The research teams jointly reviewed and compared the GSHP applications in the two countries and identified areas for future collaborations, including (1) standards and training for implementing GSHP systems; (2) new technologies that can reduce cost and improve performance of GSHP systems; and (3) policies and financial incentives to encourage wider adoption of GSHP applications.

## Conclusions

GSHP is a proven technology that utilizes clean and renewable geothermal energy, as well as the massive thermal storage capacity of the ground, to provide space conditioning and water heating for both residential and commercial buildings. It has higher energy efficiency than conventional space conditioning and water heating systems. It is estimated that 0.6 Quad Btu primary energy consumptions and 38 million tons of carbon emissions will be reduced each year if GSHP gets 10% market share in the US. More significant benefits from GSHP applications are expected in China given the huge building stocks and the severe air pollution there. However, the current market share of GSHP in both China and the US is just around 1%. While high initial cost is the primary barrier preventing wider adoption of GSHP technology in the US, it is the lack of standards governing quality of equipment, design, installation, and operation of GSHP systems that shallows the sustainable growth of GSHP applications in China. There is a strong demand in China for advanced GSHP equipment and engineering services to save energy and reduce carbon emissions and air pollutions. It is also desirable in the US to further advance the GSHP technology to maximize its cost effectiveness.

This project aims at reducing the initial cost and further improving the operational efficiency of GSHP systems by developing low-cost and performance neutral GHXs and smart controls at component and system levels. With close collaboration with the US industry partner, ClimateMaster, and Chinese counterparts in the past five years, following outcomes have been achieved, including:

- new GHXs that require 14-30% less drilling compared with conventional GHX while retaining same performance

- a first-of-a-kind research facility capable of supporting development and verification of various emerging technologies for GSHP applications in a low-risk and realistic real-building environment
- numerous case studies of various GSHP systems in both countries
- an innovative flow-demand-based pumping control, which has potential to reduce pumping energy of DGSHP systems by more than 20% (patent pending, Invention Disclosure #: 201403380, DOE S-number: S-138,004)
- a new method and enabling tool for cost effectively monitoring performance and detecting faults of DGSHP systems (Invention Disclosure #: 201403381, DOE S-number: S-138,005)
- a demonstration of the U.S. style DGSHP system in the highly visible very-low-energy-building of Chinese Academy of Building Research
- at least 12 journal and conference papers

Further, as a result of a previous BTO-funded R&D project concluded in 2013, ClimateMaster successfully launched the new Trilogy™ 45 Q-Mode™ series GS-IHP. It is the first GSHP unit ever certified by the Air Conditioning, Heating, and Refrigeration Institute (AHRI) to exceed a 45 EER performance rating. This product provides space conditioning and 100% water heating, even when space conditioning is not required.

The above technology development established a strong foundation for the next-generation of GSHP applications, which integrates the new low-cost performance neural GHXs, the advanced GS-IHP units, the smart pumping control, and the cost-effective virtual sensing based performance monitoring and fault detection system. The next-generation GSHP system will be more cost effective and capable of satisfying all the space conditioning and water heating demands in residential and commercial buildings. It will be able to optimize its operation based on thermal loads and evaluate its performance at real time. Its performance will be more visible to its owners or investors, which will enable third party financing to overcome the high initial cost barrier of the GSHP applications.

In addition to supporting the optimization and field verification needs of this project, the flexible research facility of DGSHP systems built during this project provides a first-of-a-kind facility capable of supporting other valuable research to further improve DGSHP system's energy efficiency over service life and reduce cost (e.g., fault detection and diagnostics, improved control through application of low cost wireless sensors, etc.) .With this facility, various emerging technologies can be developed and verified in a low-risk realistic real-building environment.

The outcome of this project will help overcome barriers preventing wider adoption and sustainable growth of GSHP applications in both the US and China. Further support from DOE and industrial partners is desired to commercialize the new products/technologies developed in this project to make most use of the investment in this project.

# Achieving Optimal Performance through Building Commissioning

***Joint Project***

## U.S. Partners

- **Lawrence Berkely National Laboratory**
- **California Commissioning Collaborative (CCC)**
- **Pacific Gas and Electric**
- **Interface Engineering**

## China Partners

- **Center of Science and Technology of Construction (CSTC) – Ministry of Housing and Urban-Rural Development (MoHURD)**
- **China Academy of Building Research**
- **Zhuhai Singyes Green Building Technology Co. Ltd**

## Overview

Building Commissioning (Cx) is a systematic process of ensuring that a building performs in accordance with the design intent and the owner's operational needs. It has a significant potential for reducing energy consumption in existing and new buildings. An LBNL study (Mills et al. 2009) showed that building Cx resulted in 16% energy savings in existing buildings and 13% in new construction.

The goal of this project is to promote the proper use of building Cx and ongoing Cx processes in China and the US to ensure that buildings perform as expected through the life cycle. Though building Cx has been developed in the US for nearly 40 years, it is still an emerging technology in China. Therefore, the US and China have totally different research agendas, making it challenge to develop the research topics that satisfy both countries. A compromise was made to focus on China's need to promote the adoption of building Cx. The plan is to quickly bring China up to speed, and then the two countries would work together in developing new building Cx technologies.

Over the two-year (2014-2015) project period, the US team has achieved great success in promoting building Cx in China, which leads to the decision that China will focus on building Cx in CERC-BEE 2.0. However, the US CERC-BEE 2.0 did not fund building Cx.

## Research Objectives

The objective of this project is to promote the proper use of building commissioning (Cx) and ongoing Cx processes in China and the US to ensure that buildings perform as expected through the life cycle. It is a global challenge that buildings do not perform as well in practice as intended by the design. The situation is getting worse in low-energy buildings as they employ advanced building technologies that are typically interconnected and can operate less intuitively. Cx, Testing, Adjusting and Balancing (TAB), and operating such buildings to achieve the expected performance is quite complicated. Compromises that sacrifice performance to make the system work are often made.

In the US, various Cx and TAB standards and guidelines have been well established. However, the industry practice of improperly implementing the standards and guidelines often leads to underperforming buildings. In China, the current building construction management practice splits the acceptance into several phases, which causes high building energy consumption and malfunctioning building systems. It is believed that a standardized building Cx that runs through the whole construction process will help solve the issue. Therefore, in collaboration with the US and Chinese partners, the project team will develop and demonstrate a set of Cx and ongoing Cx tools, standards and guidelines, and industry practices to ensure that the anticipated building performance is achieved and sustained through the life cycle.

## Major Accomplishments

- The new Evaluation Standard for Green Building in China adopted building Cx
- The project team published China's first building Cx handbook
- The China Association of Building Energy Efficiency (CABEE) has chosen building Cx as their top research priority and planned to set up a joint US-China Cx team to share best practices and develop standards

## Summary of Research Activities

### Year 2014

**OBJECTIVES**

- Develop and validate a set of integrated functional testing tools/templates for low-energy systems
- Demonstrate the energy savings and improved thermal comfort in real buildings in China achieved by building Cx
- Develop China's first building Cx guideline

**SUMMARY OF TASKS**

- Organized a two-day seminar in China to promote the US building Cx standards and industry practices
- Compared building Cx practices between US and China
- Reviewed the design phase Cx plan for the Xingye demonstration building in China
- Reviewed the on-going Cx plan for China Academy of Building Research demonstration building

**MAJOR FINDINGS AND OUTCOMES**

- Workshops to promote the building Cx and introduce the difference between the Chinese version of “building commissioning” and the one practiced in the US
- Increased awareness of building Cx concept in China building industry
- The new Evaluation Standard for Green Building in China adopted building Cx

Figure 1: Cx workshops in China

### Year 2015

**OBJECTIVES**

- Automate part of building Cx process to maximize benefits of building Cx
- Develop building Cx guideline for China

**SUMMARY OF TASKS**

- Evaluated the variations of controls of the five common VAV system
- Published China’s first building Cx handbook

**MAJOR FINDINGS AND OUTCOMES**

- The project team published China’s first building Cx handbook Commissioning of Buildings and Systems


Figure 2: The Building Cx Handbook

## Major Outcomes and Achievements

- The new Evaluation Standard for Green Building in China adopted building Cx and was effective on Jan 1st, 2015.
- The project team published China's first building Cx handbook Commissioning of Buildings and Systems (written in Chinese).
- The China Association of Building Energy Efficiency (CABEE) has chosen building Cx as their top research priority and planned to set up a joint US-China Cx team to share best practices and develop standards.
- The China CERC-BEE management team make the building Cx the main focus of CERC-BEE 2.0.

### Standards, Codes, and Policies Influenced

- Xiufeng Pang, Shan Liu, Yong Cao and Shilei Lv. 2015. Commissioning of Buildings and Systems. China Architecture and Building Press, Beijing China. ISBN: 9787112179473

### Workshops

- CERC-BEE Building Cx workshop, July 18-19, 2014, Zhuhai, China

### List of Publications

- Xiufeng Pang, Mary Ann Piette and Bin Hao. 2014. Commissioning, Operation, Real Time Monitoring and Evaluation of Pilot: Achieving Optimal Performance through Building Commissioning, Conference Presentation for the International Conference for Enhanced Building Operations, Sep 14-17, 2014, Beijing, China
- Xiufeng Pang, Mary Ann Piette and Philip Haves. Characterizing and Modeling the Variation of Controls of the Variable Air Volume System, to be submitted to Journal

## Collaboration

Collaboration between US and China mainly involves seminars and workshops for the practitioners in China to learn the building Cx and how building Cx would help to reduce energy consumption in buildings. The US project team have established good working relationships with Chinese partners.

## Conclusions

The US project team has successfully promoted the building Cx in China and established the trust and good working relationship with the Chinese team. The China CERC-BEE 2.0 management team has chosen building Cx as a top priority, which presents great opportunity for the US to leverage the resources in China to develop innovative building Cx technologies and influence China's building Cx standard.

# Sub Wet Bulb Evaporative Chiller

***Joint Project***

## U.S. Partners

- University of California, Davis
- Nexajoule LLC

## China Partners

- Tsinghua University
- Xinjiang Refreshing Angle Air Environment and Technology Company

## Overview

Cooling loads constitute approximately 13% of the total electricity demand in the United States. The hot dry summers in the Western United States drive cooling loads and peak demand throughout the season. The hot and dry climate creates significant potential to expand the market to incorporate evaporative cooling. Sub wet-bulb evaporative chillers (SWEC) provide one compressor-less solution capable of producing chilled water below the ambient wet-bulb condition which could be used in a radiant or fan coil system. This project completed lab testing of two sub wet-bulb evaporative chillers. The SWEC technology offers the following potential benefits:

- Chilling of supply water to lower temperatures than conventional cooling towers
- Cooling efficiencies higher than a conventional mechanical chiller
- No introduction of humidity to the building
- Ventilation air flow (in some SWEC designs)

One chiller demonstrated 0.7 – 1.7 tons of cooling capacity at a coefficient of performance (COP) between 8 and 30, while the other chiller demonstrated 3-4 tons of cooling capacity at a COP between 6 and 8.

The chillers tested as part of this project are unique in that they use indirect/direct evaporative cooling to produce chilled water below the wet-bulb temperature, as opposed to chilled air (typical in most evaporative cooling systems). Chilled water can be distributed to the building via radiant or fan-coil systems and can be easily zoned within the building. The design of the chiller allows for water and air flows to be variable in order to modulate cooling capacity to the building, and achieve higher efficiencies under lower-load conditions. Furthermore, although not tested as part of this project, chilled water can be stored to further alleviate the electricity peak demand caused by cooling buildings.

The Nexajoule chiller was demonstrated at the 2015 U.S. DOE Solar Decathlon, and the Tsinghua is being integrated into an office building system. The Nexajoule technology is being licensed by an evaporative cooling manufacturer, and WCEC has secured additional funding for residential tests.

## Research Objectives

The objectives of this project are to:

- Map the performance of existing SWECs and refine design to maximize efficiency of the chiller
- Integrate the chiller into a building hydronic system for field testing and evaluation

## Major Accomplishments

WCEC demonstrated through laboratory testing that at warm/dry outside air conditions (DB=90°F, WB=64°F) with a return water temperature of 71°F that:

- Nexajoule sub wet-bulb evaporative chiller can produce chilled water as predicted by the model at 61°F or lower with a coefficient of performance (COP) of 23 or better
- Tsinghua sub wet-bulb evaporative chiller can produce chilled water as predicted by the model at 64°F or lower and chilled air 70°F or lower with a COP of 8 or better

WCEC facilitated demonstration of the Nexajoule chiller at the 2015 U.S. DOE Solar Decathlon and is currently integrating the Tsinghua chiller into an office building radiant system located at UC Davis. Through our corporate affiliate program, WCEC introduced the proprietor of the Nexajoule technology to an evaporative cooling manufacturer who is currently pursuing licensing the technology. WCEC has secured additional research funding from the California Energy Commission for future testing and deployment of the technology in residential homes.

## Summary of Research Activities

### Year 2014 (Starting 6/24/2014)

**OBJECTIVE**

- Map the performance of existing sub wet-bulb evaporative chiller and refine design to maximize efficiency of the chiller

**SUMMARY OF TASKS**

*Lab performance characterization of two sub wet-bulb evaporative chiller prototypes documented in a technical paper*

Figure 1 illustrates the layout of the Nexajoule chiller that was tested twice in 2014. The initial results were good (COP range of 3 – 15), but the performance suffered from a large power draw at part load because the prototype had constant speed fan and water pumps. Nexajoule LLC redesigned the chiller based on the lab and modeling results. The redesign was tested in late 2014 and the COP increased to 8-30 over the same operating conditions.

*Improve fluid cooler with redesign documented*

WCEC built an iterative model, based on thermodynamic equations and validated by lab test data, to model the performance of the Nexajoule chiller at various climate conditions. Based on the modeling effort, small scale testing of possible heat exchanger redesigns were tested. The results from these tests identified the controls of the prototype as the best option for efficiency improvements.

*Secure industrial partner*

In 2014, we finalized negotiations with the Tsinghua research team and secured the Chinese industry partner, Xinjiang Technology. Xinjiang Technologies was commissioned to build a custom unit that would fit in WCEC test chamber. The chiller was successfully shipped and received in early 2015.

**MAJOR FINDINGS AND OUTCOMES**

Lab testing and modeling of the Nexajoule chiller was completed and demonstrated that switching the Nexajoule to variable speed controls increased the COP of the SWEC from 3-15 to 8-30. The unit was able to provide 0.7-1.7 tons of cooling across all test conditions.

WCEC was able to negotiate with the Tsinghua research team and secure the Chinese industry partner, Xinjiang Technology to build a custom unit that would fit in WCEC test chamber. The chiller was successfully shipped to the US and received by WCEC in early 2015.

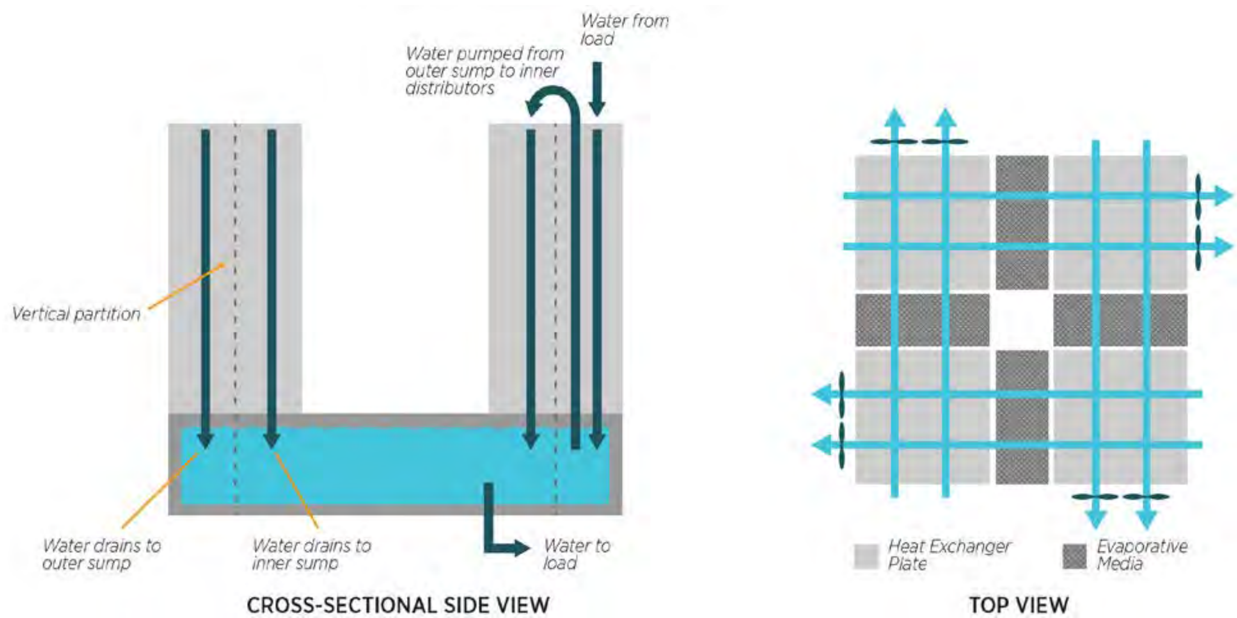



**Figure 1: Nexajoule prototype layout.**

**Figure 2: Nexajoule SWEC installed in the environmental chamber (left), Tsinghua SWEC in the WCEC laboratory (right).**

## Year 2015

### OBJECTIVES

- Map the performance of existing sub wet-bulb evaporative chiller and refine design to maximize efficiency of the chiller
- Integrate the chiller into a building hydronic system for field testing and evaluation

### SUMMARY OF TASKS

*Demonstration, through laboratory testing, that the Tsinghua Chiller meets performance targets*

WCEC completed laboratory testing and measured the water and air chilling performance of the Tsinghua chiller (Figure 3). Lab testing the chiller was a positive experience and a joint effort between WCEC and Tsinghua University. The chiller test results showed COP ranging of 6-8 over all the climate tests.

Tsinghua University built a model, based on thermodynamic equations and validated by lab test data, to model the performance of the Tsinghua chiller at various climate conditions. Modeling efforts identified varying the fan speed and controlling the ventilation air fraction as possible control methods to improve performance at part load conditions.

*Selection of field test site and installation of a chiller prototypes at the field test site(s)*

WCEC facilitated demonstration of the Nexajoule chiller at the 2015 U.S. DOE Solar Decathlon competition. Southern California Edison (SCE), who provided match funding for the project, served as advisor to Team Orange County led by UC Irvine. SCE recommended the incorporation of the Nexajoule chiller into the home's mechanical design based on lab results. All of the simulation efforts by Team Orange County found that using the Nexajoule in a radiant ceiling was the most energy efficient option. Team Orange County placed 9th overall in the competition. WCEC provided technical support for the installation and control of the chiller.

WCEC identified the California Lighting and Technology Center (CLTC) as a demonstration site for the Tsinghua chiller. The CLTC has an existing six zone radiant floor system that currently is only used for heating. WCEC designed the retrofit solution and selected a contractor to isolate one of the six radiant zones to provide cooling during the summer months. WCEC continues to move forward with the installation, which is scheduled to occur in mid-2016. WCEC has identified additional funding from Pacific Gas and Electric (PG&E) to complete the evaluation of the field demonstration.

*Peer reviewed publication of Nexajoule and Tsinghua field test results*

WCEC submitted a paper to ACEEE which has been accepted as a peer reviewed publication in ACEEE's 2016 Summer Study.

**MAJOR FINDINGS AND OUTCOMES**

- Lab testing and modeling of the Tsinghua Chiller was completed. The results demonstrated that the chiller provided 3-4 tons of cooling with a COP of 6 – 8 across all test conditions.
- WCEC facilitated demonstration of the Nexajoule chiller at the 2015 U.S. DOE Solar Decathlon competition. Team Orange County, through simulation, determined using the Nexajoule in a radiant ceiling was the most energy efficient option and placed 9th overall in the competition.
- WCEC identified a site, designed the retrofit solution, selected a contractor, and secured addition funding through PG&E for the field demonstration of the Tsinghua chiller.
- WCEC introduced the proprietor of the Nexajoule technology to an evaporative cooling manufacturer who is currently pursuing licensing the technology.

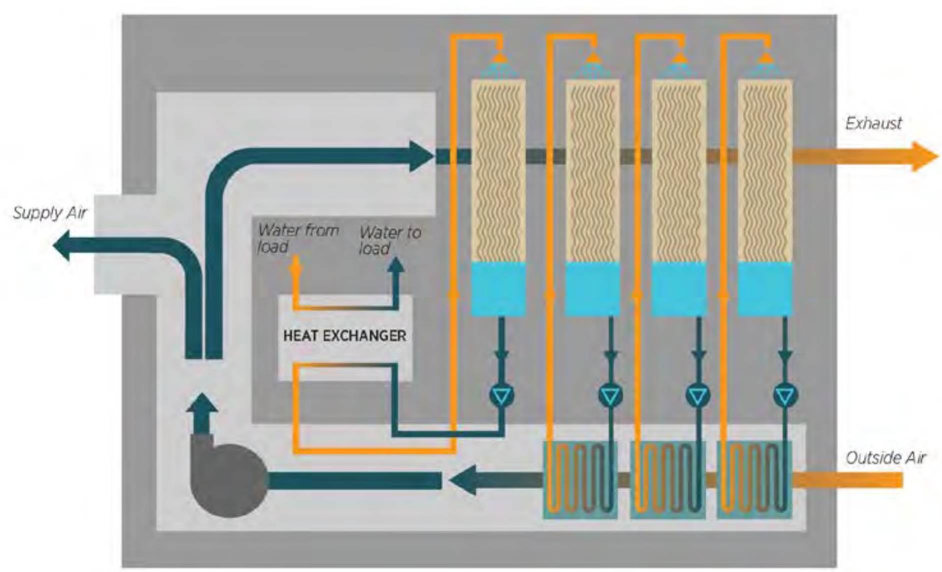



**Figure 3: Tsinghua chiller layout.**

Figure 4: (Left) Nexajoule at 2015 U.S. DOE Solar Decathlon, (right) Mock-up of Tsinghua chiller installation at CLTC.

## Major Outcomes and Achievements

### Workshops

- WCEC 2015 Affiliate Forum, May 20th 2015, Davis, California
- 36th Utility Energy Forum, May 15th 2015, Lake Tahoe, California

### List of Publications

- Pistochini, P., Garcia, J., Xie, X., Xiaoxiao, F., Jarvis, E., Sub Wet-Bulb Evaporative Chillers for Building Cooling Systems. American Council for an Energy-Efficient Economy. Summer Study 2016

## Collaboration

WCEC worked most closely with Nexajoule in the testing the Nexajoule technology, and then looked for potential larger scale manufacturing partners for Nexajoule. Integrated Comfort, a WCEC affiliate partner, is currently licensing the Nexajoule technology. Integrated Comfort is a partner in the California Energy Commission funded project that will demonstrate the Nexajoule technology in residential homes.

Professor Xiaoyun Xie and graduate student Feng Xiaoxiao visited UC Davis to assist in the testing of their chiller. They were very involved and monitored every aspect of the testing. We maintained the collaboration since working on the joint ACEEE publication and the field demonstration.

## Conclusions

WCEC demonstrated through laboratory testing that at warm/dry outside air conditions (DB=90°F, WB=64°F) with a return water temperature of 71°F that:

- Nexajoule sub wet-bulb evaporative chiller can produce chilled water as predicted by the model at 61°F or lower with a COP=23 or better
- Tsinghua sub wet-bulb evaporative chiller can produce chilled water as predicted by the model at 64°F or lower and chilled air 70°F of lower with a COP=8 or better

WCEC facilitated field demonstrations the Nexajoule and Tsinghua chillers as well as identified one commercialization opportunity for the Nexajoule chiller. WCEC has secured additional funding from the California Energy Commission and PG&E to complete field demonstrations of both the Nexajoule and Tsinghua technologies.

# Commercial Building Energy Efficiency Standard

***Joint Project***

## U.S. Partners

- Lawrence Berkeley National Laboratory
- Lutron Electronics

## China Partners

- China Academy of Building Research
- LUO Duo
- Xingye Solar

## Overview

Buildings in the U.S. and China consumed about 40% and 30% of primary energy in 2010, respectively. In comparison with the U.S. where energy is primarily consumed by existing buildings, new construction is the main driver of commercial building energy use in China. From 1996 to 2008, total floor space of commercial buildings increased from 2.8 billion m2 to 7.1 billion m2. Now, approximately 0.5 billion m2 of new commercial building floor space is built every year.

In the U.S. building energy efficiency standards play an important role in reducing energy use. ASHRAE has maintained and updated commercial building energy standards, ASHRAE-90.1, since the 1970s. The most recent update of the energy standards in 2010 achieved 30% in energy savings compared with the baseline defined by ASHRAE 90.1-2004.

Comparable to the U.S. commercial building energy standards, China issued its own standards for commercial (public) buildings (GB50189) in 1993, with an initial emphasis to reduce energy consumption in hotels. After that, the standards were revised to include other commercial building types. The last update in 2005 mandated that commercial buildings be 50% more efficient than a baseline defined by 1980s building characteristics. (Buildings in China were constructed without rudimentary energy efficiency measures. As a result, increasing energy efficiency by 50% from a very inefficient building is not difficult to achieve.) The current 2014 update mandates that new commercial construction will be 65% more efficient than that baseline. Policy makers and standards developers are emphasizing this 65% efficiency goal, but energy savings evaluation and validation have not yet been studied for the new standards.Developing energy efficient codes and standards is estimated to save 36 tons of CO2 emission in the U.S. In China, the commercial building energy standard is estimated to save 249 mtce primary energy from 2010 to 2030.

This research project analyzes the performance of the new commercial building standard in China. The performance of the Chinese standard is compared with ASHRAE 90.1-2013 and differences are discussed. The tech-economic performance of the new Chinese standard is evaluated. And finally, the next version of the Chinese commercial building standard is discussed by learning from the experience from ASHRAE 90.1.

## Research Objectives

Evaluate the energy and cost-effective performance of the new Chinese commercial building energy standard. Use an energy modeling approach to quantify performance and contrast the performance of the Chinese commercial building standard with the U.S. one. Summarize and compare experience of code and standard development in China and the U.S.

## Major Accomplishments

Chinese buildings on average consume much less energy than those in the U.S. and Europe; however, this is due to differences in operation practices and not necessarily because the building codes and standards in China are more stringent. Code-compliant Chinese commercial buildings use more energy than the U.S. and could use up to 80% more, if all operated in U.S. conditions. Commercial buildings operated under the Chinese code will have higher site energy use intensity (120 kWh/m2 in 2015) compared to that of the current version of the U.S. standard ASHRAE 90.1-2013 (100 kWh/m2) when differences in operating practices are taken into account (Figure 1)[1.] If the Chinese buildings defined by the code are operated in the same way as U.S. buildings, they will have even higher energy use intensity values (180 kWh/m2 in 2015). Similarly, if U.S. buildings operated using Chinese settings, then an additional 10% energy would be saved (Feng et al 2014).

## Summary of Research Activities

### Year 2014

**OBJECTIVE**

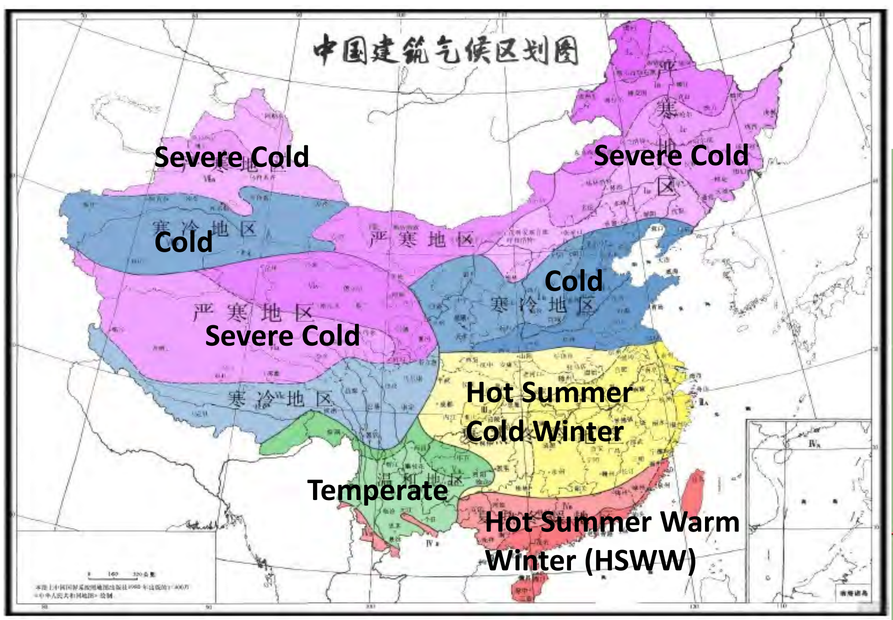
- Develop one Chinese reference building to evaluate the commercial building energy standard's performance in comparison with ASHRAE 90.1-2013

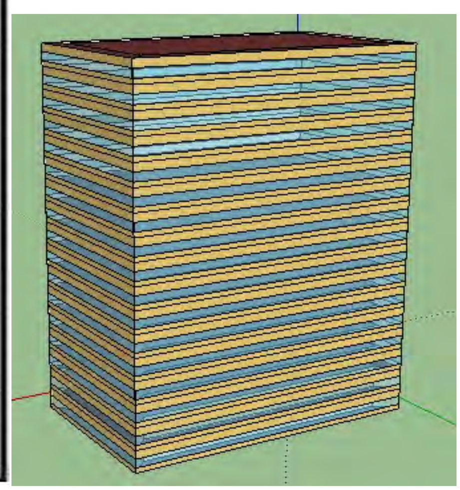
**SUMMARY OF TASKS**

- Reviewed the new updated Chinese commercial energy standards and evaluate compliant building energy performance
- Developed a Chinese office reference building model based on available Chinese buildings data

**MAJOR FINDINGS AND OUTCOMES**

A large commercial office building model is developed to evaluate the performance of the Chinese commercial building energy standard. The Chinese reference buildings were developed using common Chinese building systems and characteristics described in the 2005 and 2014 building standards. Simulation analysis was conducted to compare the energy savings of the 2014 standard with previous versions and ASHRAE 90.1 performance. The research finds that the new commercial building energy standard is 62% efficient than the 1980's baseline, which is 26% efficient than its previous version in 2005. Recommendations are provided for revising and improving the new standard.



### Year 2015

**OBJECTIVE**

- Develop Chinese reference buildings to evaluate the commercial building energy standard's energy and tech-economic performance. Understand the gaps between Chinese commercial standard and the U.S. one, and further explore the reasons behind the performance gaps. Develop a few requirements for future standard update.

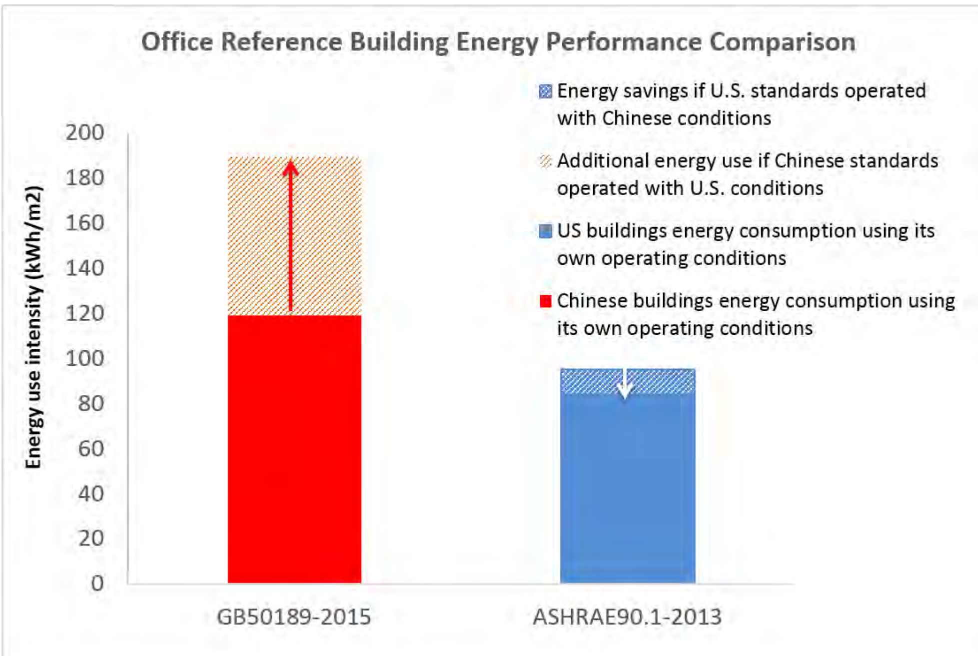
[1] The ASHRAE 90.1 estimated building performance is based on a study of office buildings built in accordance with the Department of Energy code program. Both China and the U.S. buildings here include major regulated end use such as lighting, heating, ventilation and air-conditioning (HVAC), plug load, water heating. However, Chinese codes and standards often only include lighting and HVAC for performance evaluation.

**SUMMARY OF TASKS**

- Developed Chinese reference buildings for government buildings, and shopping malls
- Evaluated compliant building energy performance for government buildings, and shopping malls, and compare with the performance of 2005 standard
- Based on ASHRAE 90.1 experience, identified gaps between ASHRAE 90.1 and GB50189. Summarize areas which can be upgraded in the future for building energy standards in both U.S. and China. Disseminate the findings to key stakeholders.

**MAJOR FINDINGS AND OUTCOMES**

Based on 2014 work, two more reference building models (government office building, and shopping mall) are developed. A comprehensive analysis of the 2015 Chinese commercial building energy standard is conducted. The analysis not only conducted the energy performance but also the standard's cost-effectiveness. It is found that the new commercial buildings standard can achieve simple pay-back period of approximate 4 years in Chinese market. This study also evaluate the reasons of the performance gaps between the Chinese standard and U.S. one. Different operating conditions and thermal comfort criteria are considered, when analyzing the performance gaps. Finally, this study provide some key requirements for future standards updates in China.




## Major Outcomes and Achievements

### Standards, Codes, and Policies Influenced

- GB 50189-2015, Chinese commercial building energy efficiency standard

### Workshops

- Oct 2013, APEC Net/Nearly Zero Energy Building Workshop (1), Beijing
- Oct 2014, APEC Net/Nearly Zero Energy Building Workshop (2), Beijing
- Oct 2014, Chinese commercial building standard revision meeting and expert review, Beijing 2014
- Aug 2015, APEC Net/Nearly Zero Energy Building Workshop (3), Montreal Canada
- Apr 2014, APEC Net/Nearly Zero Energy Building Workshop (4), Taiwan

### List of Publications


- ZHAO Shanguo, Wei Feng, Shicong Zhang, Jing Hou, Nan Zhou, Mark Levine, Energy Savings and Cost-benefit Analysis of the New Commercial Building Standard in China, Procedia Engineering Volume 121 (2015): 317-324
- ZHOU Nan, Nina Khanna, Wei Feng, China's Building Energy Use, ASHRAE Journal 56 (7) Jul 2014, pp 26- 28

- ZHANG Shicong, Wei Xu, Yiqiang Jiang, Wei Feng, and Deyu Sun. "Research on Demonstration Project Technology Roadmap of Zero Energy Buildings Abroad (in Chinese)." HV&AC 44, no. 1 (2014).
- FENG Wei, Nan Zhou, Stephane de la Rue du Can, Michael Bendewald, Ellen Franconi, Building Energy Codes in China: Recommendations for Development and Enforcement, Paulson Institute Annual Conference on Urban Sustainability, October 2015, Beijing, China
- ZHAO Shanguo, Wei Feng, Shicong Zhang, Jing Hou, Nan Zhou, Mark Levine, Energy savings and cost-benefit analysis of the new commercial building standard in China, The 9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC), The 3rd International Conference on Building Energy and Environment (COBEE), July 2015, Tianjin, China
- WU Yong, Jing Hou, Nan Zhou, Wei Feng. Research on an Energy-Efficiency Improvement Roadmap for Commercial Buildings in China. Proceedings of the European Council for An Energy-Efficient Economy 2015 Summer Study on Energy Efficiency. Club Belambra Les Criques, Presqu'île de Giens Toulon/Hyères, France: ECEEE
- FENG Wei, Ke Huang, Shicong Zhang, Mark Levin, Nan Zhou. "Evaluation of Energy Savings of the New Chinese Commercial Building Energy Standard", Proceedings of the American Council for An Energy-Efficient Economy 2014 Summer Study on Energy Efficiency. Washington DC: ACEEE.


## Collaboration

This study collaborates closely with participating U.S. industrial partners, which play various roles. For example, SOM worked with LBNL to understand how the new standard impacts their design in Chinese market and how SOM can excel the national standard requirement and deliver better design for customers. Carrier provided detailed technologies performance and cost data and worked with LBNL team to conduct cost-benefit analysis of the standard. LBNL would like to continue work with U.S. industry partners to understand how codes and standards development can impact U.S. technologies deployment in China and what energy savings could new codes and standard bring to the market.

LBNL works closely with China Academy of Building Research (CABR) and MOHURD in this project. CABR help LBNL collected basic building characteristic data which were used for the Chinese reference building development. Data sharing is essential in CERC projects, and researchers managed to share some data between the Chinese and U.S. teams.

## Conclusions

Codes and standards are important to ensure energy efficient technologies adopted in market. This project demonstrated that U.S. and Chinese researchers can work together to develop a new energy efficient standard and evaluate the standard's performance collaboratively. The methodologies developed by U.S. DOE on developing commercial reference buildings for codes and standards performance evaluation is adopted here for the Chinese standard development. The joint research shows that the new Chinese standard has achieved energy savings of 62% compared with the 1980's baseline (or 26% compared to its previous 2005 version), and has average simple payback period of 4 years. This study was the first to explain, in detail, the performance differences between the Chinese standard and ASHRAE 90.1-2013.

# Microgrid in Buildings

***Joint Project***

## U.S. Partners

- Lawrence Berkeley National Laboratory
- C3 Energy

## China Partners

- Tianjin University
- Tongji University
- LUO Duo
- Xingye Solar

## Overview

Microgrids enable integrated distributed energy building systems, and are natural hosts for renewable energy. They manage distributed energy resources to be optimally utilized in buildings and communities to meet the load requirement. Optimizing microgrid performance by planning potential distributed energy resources (DER) and dispatching energy technologies to operate synergistically is very important for buildings and communities design and operation.

Distributed energy resources utilization in buildings reduces primary energy consumption and CO2 emissions. This research finds that DER technologies have economic and environmental competitiveness potential, especially for commercial buildings in both countries. In the U.S., the average expected energy cost savings in commercial buildings from the tool DER-CAM developed by this study, suggested is 17%, while in Chinese buildings is 12%. The average CO2 emission reduction potential is about 19% for U.S. commercial buildings.

This research started with development of a microgrid optimization tool and its user interface. Then the developed tool was applied to individual buildings' distributed energy microgrid system planning and software as a service (SAAS) was used to deploy building level distributed energy system planning. In year 4, SAAS was used to deliver optimal control schedule of microgrid system for a pilot building in New Mexico and Tianjin China. Finally, the work was further expanded to conduct community energy system planning with multiple buildings.

## Research Objectives

Optimize building and community level microgrid system planning and operation by employing SAAS method to deliver optimal solution for distributed energy system controls in pilot buildings in China and the U.S.

## Major Accomplishments

DER-CAM was able to find an economically feasible mixed DER technology solution in most U.S. cities. The average energy cost savings of the optimal solutions is 17%. The exception is Seattle, where, under the studied circumstances, no economic improvement is achievable by investment in DER. The electricity tariff influence is seen here, since there is only minimal demand charging and the volumetric rate is relatively low and only slightly variable, behaving almost as a flat tariff. Also, Seattle features a low natural gas tariff, blocking investment in solar thermal, which has revealed attractive savings in other reference cities.

If the above mentioned results are looked at from a sensitivity perspective, cities with natural gas prices under 0.02-0.03 $/kWh show no inclination toward solar thermal adoption but rather other heat generation DER options. Cities with average electricity rates over 0.07 $/kWh invest in DER generation. To understand if adoption is going to take place under these values is complex, depending on climate, consumption patterns, and also on the way power is charged to the customer. The group composed of Las Vegas, Duluth, Phoenix and Miami, where the average electricity price is 0.05 $/kWh, exemplifies this situation. Looking at the spark spread in each of the cities (see Figure below), it seems clear that at least for high values of spark spread (defined here as over 0.05 $/kWh), the energy savings from DER adoption are always significant (over 20%). These are the cases of Fairbanks, Los Angeles, Albuquerque and San Francisco. For lower spark spread values, this relation is not as clear.

From a $CO_2$ abatement perspective, the significant potential of DER is made clear in the Figure below. The average emissions reduction in the American group of buildings is 19%, but customers in Phoenix and Atlanta achieved values of 40% and more, due to pronounced suggested investments in PV. Increased efficiency in the usage of fuel facilitated by CHP is also a relevant factor in emissions reduction, notably in Chicago, but also in Las Vegas, San Francisco, Fairbanks and Duluth. In Miami, where strong investments in CHP and battery storage are suggested, the reduction in $CO_2$ emissions is interestingly low, around 8%. The cause is high investments in electrical storage, which uses utility electricity to charge batteries, resulting in an increase of grid marginal emissions.

## Summary of Research Activities

### Year 2011

**OBJECTIVE**

- Expand DER-CAM capacity with heat pump models integrated in distributed energy system. Develop a DER-CAM webopt interface

**SUMMARY OF TASKS**

- Developed heat pump model in DER-CAM and integrate the model in distributed energy system optimization
- Developed a web interface for DER-CAM in both Chinese and English

**MAJOR FINDINGS AND OUTCOMES**

The heat pump model in DER-CAM has the capability to model air-source heat pump and ground source heat pump. The heat pump has the capability of working in heating mode and cooling mode. DER-CAM optimization can take the heat pump model into its energy system balance, and compare its cost and performance with other distributed energy technologies.

### Year 2012

**OBJECTIVE**

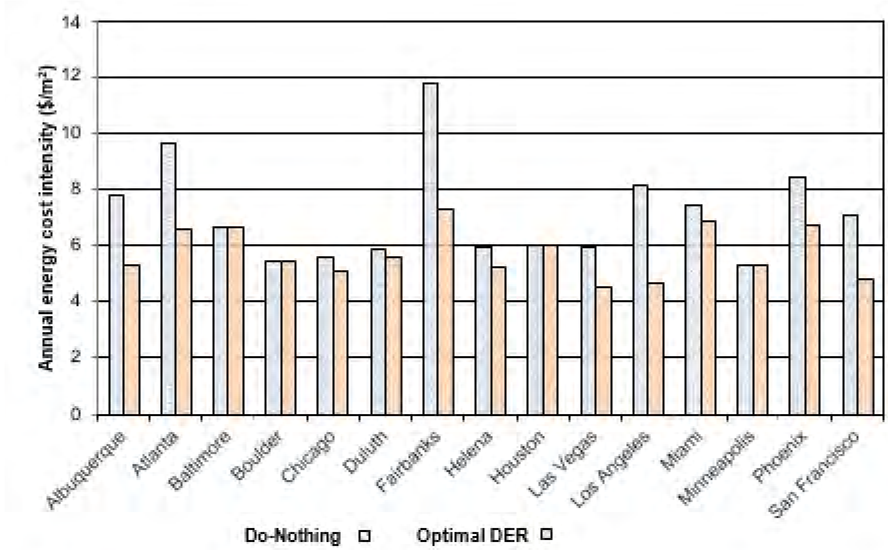
- Conduct distributed energy source technologies adoption potential analysis in buildings
- Evaluate energy cost savings and $CO_2$ reduction potential for Chinese and U.S. buildings across different climate zones

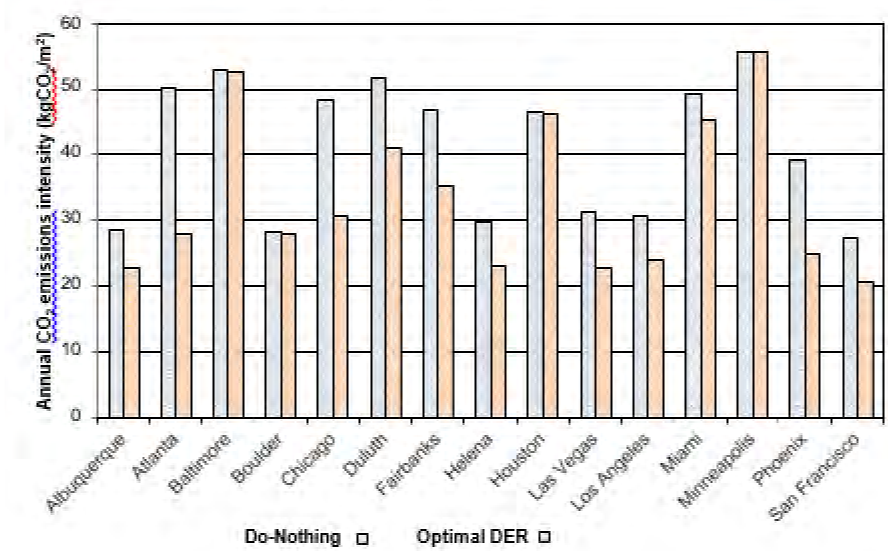
**SUMMARY OF TASKS**

- Evaluated Chinese buildings cost savings and $CO_2$ reduction potential for adopting distributed energy system
- Evaluated U.S. buildings cost savings and $CO_2$ reduction potential for adopting distributed energy system

**MAJOR FINDINGS AND OUTCOMES**

Found that DER technologies have economic and environmental competitiveness potential, especially for commercial buildings in hot and cold climates of both countries. In the U.S., the average expected energy cost savings in commercial buildings from DER CAM's suggested investments is 17%, while in Chinese buildings is 12%. The average $CO_2$ emission reduction potential is about 19% for U.S. commercial buildings. The largest $CO_2$ reduction potential is 40% in U.S. commercial buildings.




## Year 2013

**OBJECTIVE**

- Provide training for using DER-CAM Webopt in China and apply the tool for the distributed microgrid solution in a few Chinese pilot projects

**SUMMARY OF TASKS**

- Provided DER-CAM webopt training in Tongji University and Tianjin University in China
- Applied DER-CAM to optimize energy system operation in building 26 of Tianjin University

**MAJOR FINDINGS AND OUTCOMES**

DER-CAM and its web interface Webopt were well disseminated through training. There are 100+ users signed up in China using DER-CAM for their buildings' distributed energy system planning. In Building 26 pilot project, the research demonstrated a methodology developed by LBNL that used SAAS combined with load forecast to dispatch energy system operation in a building. The method was proven to be effective to provide day-ahead optimal control schedules for buildings.

## Year 2014

**OBJECTIVE**

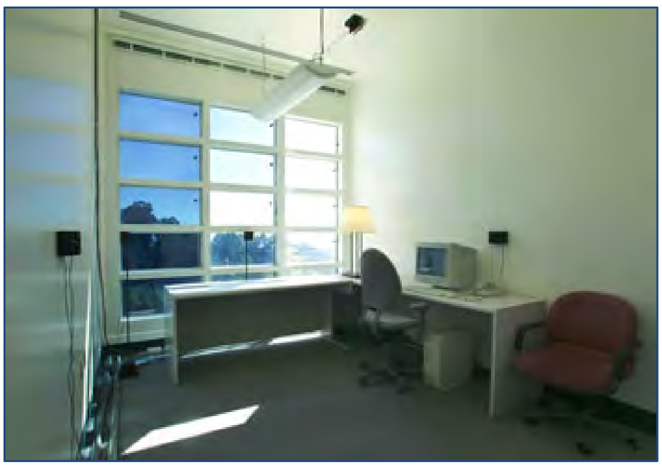
- Conduct optimal control of buildings with distributed energy system and electrochromic windows. The Mechanical Engineering building in University of New Mexico optimal predicted control to minimize building operation energy cost

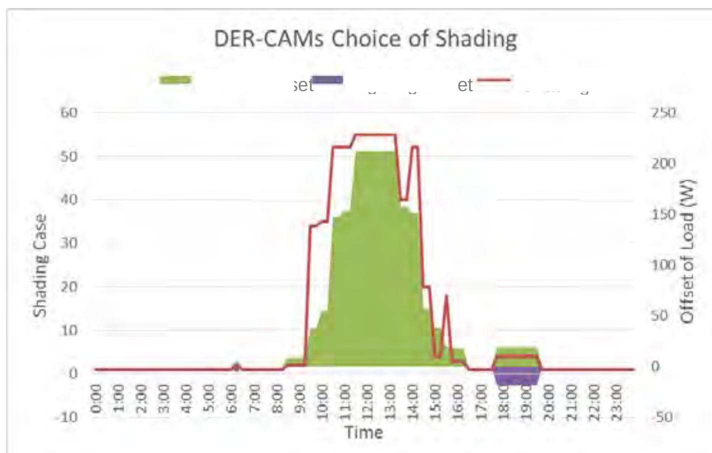
**SUMMARY OF TASKS**

- Electrochromic window optimal controls in Building 71T, LBNL
- Used SAAS method to control the optimal charging and discharging of the cooling storage system in Mechanical Engineering building of UNM

**MAJOR FINDINGS AND OUTCOMES**

The Electrochromic window control is a joint CERC-BEE project between microgrid and window project teams. In this study, the shading level of electrochromic windows were controlled to minimize the testbed energy costs, by trading off the visible light transmitted through the windows and savings of artificial lighting with introduced cooling load. Typical electrochromic window operation strategies are provided based on predicted control method. In UNM, the cooling storage tank in Mechanical Engineering building was optimized so that the building can prioritize using its local generated solar thermal for absorption and acquire campus loop district heating and cooling energy supply. The modeled results show that the optimal control strategies can save approximately 20% of the building's energy operation cost.






## Year 2015

**OBJECTIVE**

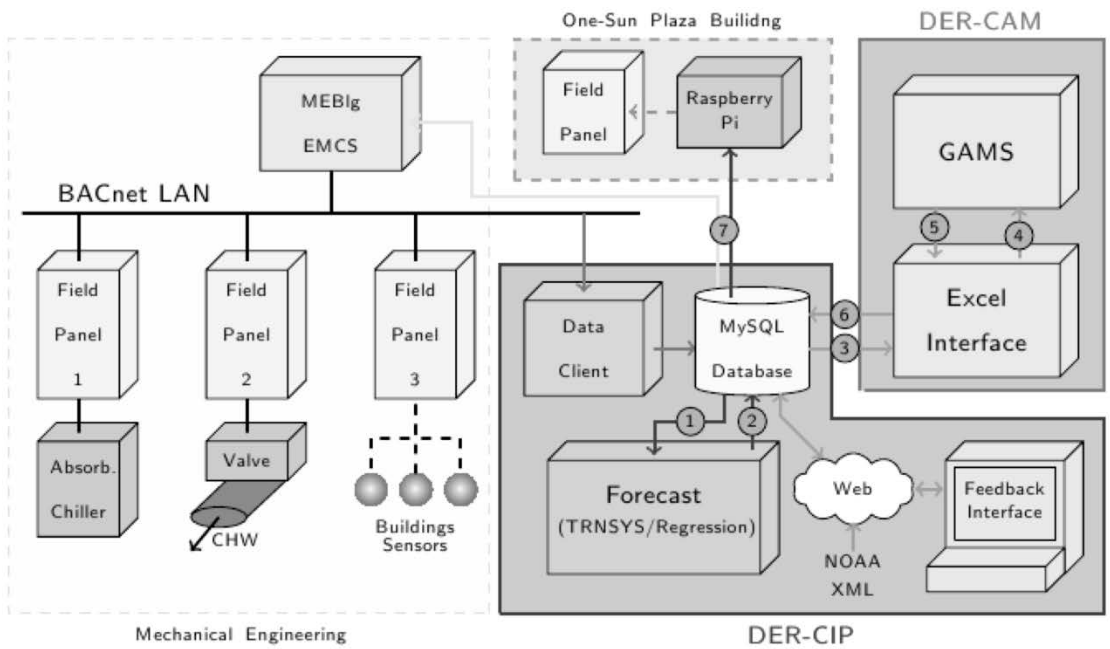
- Conduct detailed control of the energy system in Mechanical Engineering building in University of New Mexico considering different model predictive control methods. Develop a district level energy system planning tool

**SUMMARY OF TASKS**

- Modeled predictive control of UNM Mechanical Engineering buildings and compared the control results with actual measurement results. Developed robust control methods, when errors were introduced in actual control
- Further developed a district level optimization tool for district energy system optimization

**MAJOR FINDINGS AND OUTCOMES**

More robust control methods are introduced to UNM case. The model predictive control compared load forecast using a regression method and TRNSYS tuned model predictive control. Errors are discussed and analyzed how they impact optimization results. The district model further expand the optimization capabilities by taking lossage from pipes and aggregate load at individual building level through pipeline topology.




## Major Outcomes and Achievements

### Standards, Codes, and Policies Influenced

- China's 12th Five Year Plan microgrid development plan

### Products Launched

- DER-CAM webopt, with free public open access. Approximately 300+ users have registered and use it around the world.


### Workshops

- April 2012, Tongji University, Shanghai, China
- August 2012, CERC conference, Sanya, China
- August 2012, Zhuhai, China
- Oct 2012, Tianjin University, Tianjin, China
- Oct 2013, Tianjin University, Tianjin, China
- Nov 2014, Tianjin University, Tianjin, China
- Nov 2015, Tianjin University, Tianjin, China

### List of Publications


- Yan Ding, Zhaoxia Wang, Wei Feng, Chris Marnay, Nan Zhou, Influence of occupancy-oriented interior cooling load on building cooling load design, Applied Thermal Engineering, Available online 10 December 2015
- MENDES Gonçalo, Wei Feng, Michael Stadler, Jan Steinbach, Judy Lai, Nan Zhou, Chris Marnay, Yan Ding, Jing Zhao, Zhe Tian et al. "Regional analysis of building distributed energy costs and CO2 abatement: A U.S.–China comparison." Energy and Buildings 77 (2014): 112-129
- DEFOREST Nicholas, Gonçalo Mendes, Michael Stadler, Wei Feng, Judy Lai, and Chris Marnay. "Optimal Deployment of Thermal Energy Storage under Diverse Economic and Climate Conditions." Applied Energy 119 (2014): 488-496
- BARSUN Hans, Leila Ghanbari, and Andrea Mammoli, Salman Mashayekh, Wei Feng, and Chris Marnay, Software-as-a-Service Optimal Scheduling of New Mexico Buildings, C. Birk Jones, Matthew Robinson, Proceedings of the European Council for An Energy-Efficient Economy 2015 Summer Study on Energy Efficiency. Club Belambra Les Criques, Presqu'île de Giens Toulon/Hyères, France: ECEEE
- DEFOREST Nicholas, Gonçalo Mendes, Michael Stadler, Wei Feng, Judy Lai, and Chris Marnay. Thermal Energy Storage for Electricity Peak demand Mitigation: A Solution in Developing and Developed World Alike In ECEEE 2013 Summer Study 3–8 June 2013, Belambra Les Criques, France. Belambra Les Criques, France, 2013
- FENG Wei, Goncalo Mendes, Shi Wang, Michael Stadler, Jan Steinbach, Judy Lai, Nan Zhou, Chris Marnay, A US and China Regional Analysis of Distributed Energy Resources in Buildings, June 2013, Berkeley: Lawrence Berkeley National Laboratory, 2014
- FENG Wei, Nan Zhou, Chris Marnay, Michael Stadler, Juddy Lai, Qibo Liu, and R. Fan, "Building Distributed Energy Performance Optimization for China – a Regional Analysis for Building Energy Costs and CO2 Emissions", ACEEE 2012 Summer Study, Asilomar, CA, 08/2012


## Collaboration

LBNL mainly works with C3 and Demand Energy in using DER-CAM for their specific application. LBNL also works closely with Tianjin and Tongji University. Visiting researchers from China are exchanged to LBNL to work on modelling and pilot projects. Joint publication is produced through the collaboration.

## Conclusions

Microgrids were found to be effective in reducing building energy cost and CO2 emissions. The regional study conducted by this research showed that commercial buildings have great potential to adopt DER technologies and microgrid systems. A maximum of 40% CO2 reduction was observed in both countries from applying distributed energy technologies in commercial buildings. Finally, this study demonstrated how to use SAAS methods to do model predictive optimal control for a few pilot buildings in China and the U.S.

# Hybrid Ventilation Optimization and Control Research and Development

***Joint Project***

## U.S. Partners

- Massachusetts Institute of Technology

## China Partners

- Tongji University
- Chongqing University
- Tianjin University
- Zhuhai Singyes Green Building Technology Co., Ltd

## Overview

MIT has been improving CoolVent, a software tool that can determine thermal and flow conditions in naturally ventilated buildings that is fast, accurate and easy to use. CoolVent is intended to be especially useful during the early stages of the building design process, when the geometry and other general characteristics of a building are not well known or defined. As part of CERC, new models to predict the air thermal stratification, radiative view factors and the two-way flowrate of air during transient simulations have been developed and incorporated into CoolVent. These additions allow the computation and evaluation of comfort conditions in a naturally ventilated space with a degree of accuracy unmatched in any other software based on multizone networks. A knowledge of the comfort conditions is critical when designing new energy-efficient, comfortable buildings. As part of this project, the temperature and airflow rate in two buildings, one in the US and one in Japan, have been measured and compared against CoolVent. Results show good agreement, with a typical error below 15%. Conditions in another building in China will be measured during the summer of 2016. In 2014 MIT pointed out a major flaw in the design of this building in China that would compromise the performance of natural ventilation. On the basis of our work, together with industrial and academic colleagues in China, the design of the façade of this building was modified to address this problem. Monitoring of this building will ensure that these modifications improve the performance of natural ventilation. Finally, CoolVent was used to estimate the potential of natural ventilation to provide comfort conditions and energy savings in commercial buildings in different climate regions of the US. Unfavorable climate regions, such as Miami, benefit with energy savings as small as 15% when using natural ventilation, while cities with a more favorable weather, such as Los Angeles, can reduce energy consumption by 70%.

## Research Objectives

The goal of this project is to promote the widespread application of natural ventilation for energy efficiency and improved indoor climatic conditions. To do so, the next objectives were proposed for CERC-BEE 1.0:

- To determine the potential of natural ventilation to provide comfortable conditions that will reduce or eliminate the need for air conditioning over the important climatic zones in China and the US.
- To identify methods and cooling techniques based on natural ventilation that are applicable to different climate zones in China and the US by monitoring demonstration projects in these countries.
- To develop fast but accurate computational design tool that can be easily and confidently used in new or retrofit designs of naturally ventilated buildings, to promote the applications of this technology in new and existing buildings that can benefit from it.
- To disseminate results and make design tool widely available to enhance the proper use of natural ventilation for energy efficiency and comfort.

## Major Accomplishments

Developed, improved and validated CoolVent, a design and analysis tool for naturally ventilated buildings. Research conducted as part of the CERC program increased the capabilities of CoolVent, which makes CoolVent unique in many aspects among other simulation tools for ventilation in buildings. CoolVent can predict the thermal stratification of the air, thus allowing for a more accurate assessment of the comfort conditions in a building, than it is available in other tools based on a single uniform temperature per zone. Control strategies for naturally ventilated buildings have been optimized and the results incorporated into CoolVent. This allowed us to analyze the potential of natural ventilation (percentage of time that natural ventilation can be used to keep occupants comfortable) in different cities in the US for different representative commercial buildings. Thanks to its many capabilities, CoolVent was used as part of the design of the ventilation system and strategy of a commercial building being built in Zhuhai, China. On the basis of our work, together with industrial and academic colleagues in China, the design of the façade of this building was modified to improve the performance of its ventilation system.

## Summary of Research Activities

### Year 2011

**OBJECTIVES**

- To determine the potential of natural ventilation to provide comfortable conditions that will reduce or eliminate the need for air conditioning over the important climatic zones in China and the US
- To promote the widespread application of this technology for energy efficiency and improved indoor climatic conditions

**SUMMARY OF TASKS**

The project began by contacting our partners in China and agreeing to the general objectives and scope of the project. As per the requirements of the CERC-BEE administration, the US-China team wrote and signed the 10 point agreement of the project.

### Year 2012

**OBJECTIVES**

- To determine the potential of natural ventilation to provide comfortable conditions that will reduce or eliminate the need for air conditioning over the important climatic zones in China and the US
- To promote the widespread application of this technology for energy efficiency and improved indoor climatic conditions

**SUMMARY OF TASKS**

*Improvement of CoolVent*

At the beginning of this year, CoolVent was able to simulate buildings exclusively under natural ventilation mode. However, most commercial buildings incorporate both natural and mechanical ventilation systems to ensure comfort conditions during occupied hours. Moreover, the potential demonstration buildings identified for this project have both ventilation systems (dual or hybrid mode). Thus, CoolVent was improved to be able to simulate buildings that use both natural and mechanical ventilation. Achieving adequate control of the system was the main challenge identified. Tasks carried out during this year are listed below:

- Added capability to simulate fan-assisted natural ventilation, a strategy that is becoming more prevalent in hybrid ventilation systems
- Added capability to calculate energy consumption by fans, dual-mode operation with natural ventilation or mechanical chillers, and the implementation of an economizer ventilation mode
- Included new control system for the fan based on comfort conditions (temperature), indoor and outdoor conditions

*Monitoring of buildings*

US research team identified a demonstration building that can be used to validate CoolVent. Once CoolVent has been validated, it will be used to analyze and, if applicable, improve the performance of this building.

- Monitoring demonstration building: The Artists for Humanity Center in Boston, MA. Temperature, humidity and airflow measurements were performed
- Results from monitoring experiment compared to CoolVent, showing good agreement

- Began experimental monitoring of building in downtown Tokyo. This building was designed using CoolVent

**MAJOR FINDINGS AND OUTCOMES**

- Possibility to simulate fan assisted natural ventilation in CoolVent, allowing us to simulate the Artists for Humanity EpiCenter building
- Comparison between CoolVent and experimental results for the Artists for Humanity EpiCenter building showed excellent agreement (within 15%)
- Simulation using CoolVent showed potential problems in the Artists for Humanity EpiCenter building regarding night cooling control

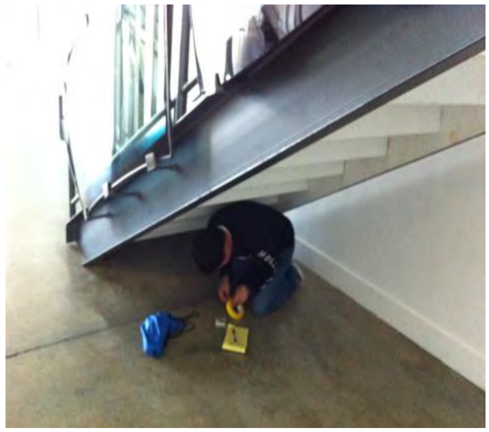


Figure 1: Setting thermal mass temperature measurement probes at The Artists for Humanity Center in Boston

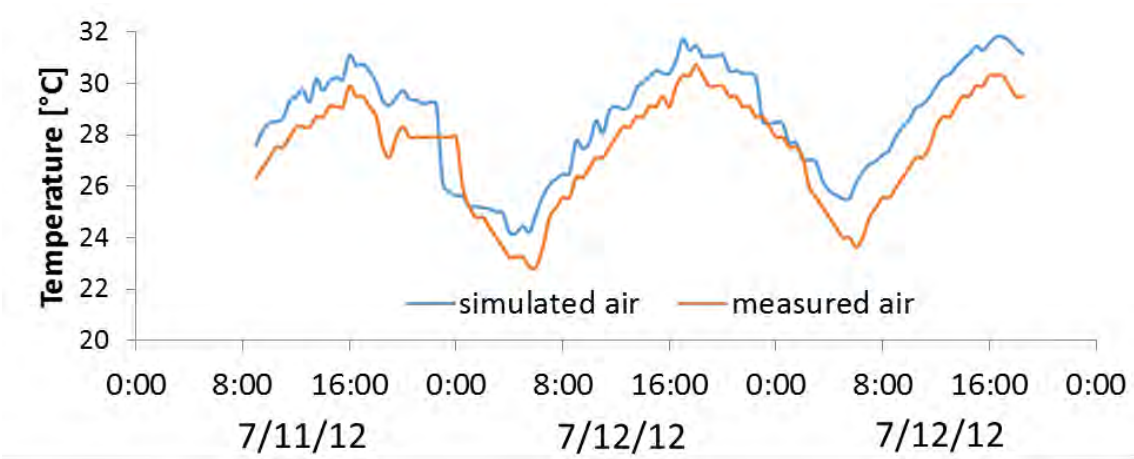



Figure 2: Comparison between CoolVent and experimental measurements for the air temperature at The Artists for Humanity Center in Boston. This graph shows that CoolVent can be used to predict the temperature of a naturally ventilated space. Experimental validation of a building simulation tool is critical to be used with confidence.

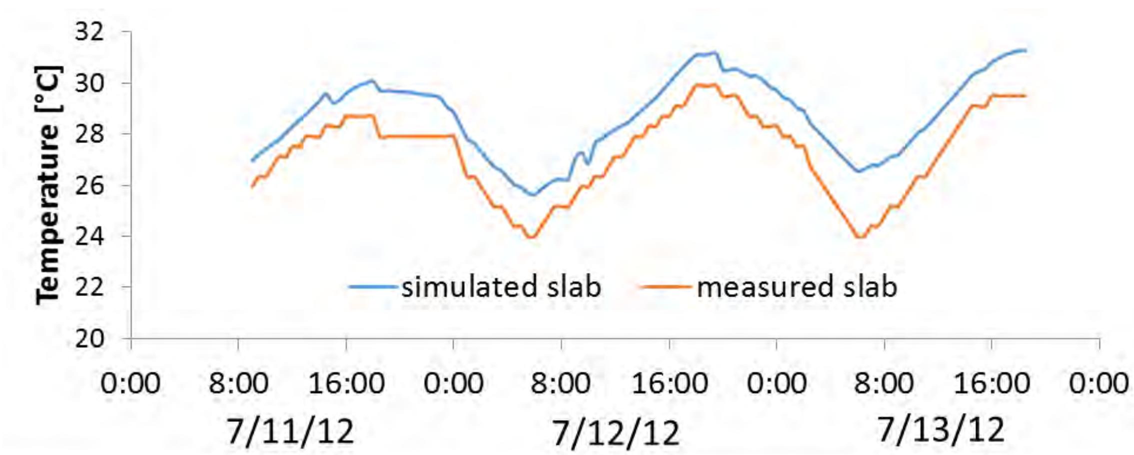



Figure 3: Comparison between CoolVent and experimental measurements for the thermal mass temperature at The Artists for Humanity Center in Boston. This graph shows that CoolVent can be used to predict the temperature of the thermal mass in a naturally ventilated space.

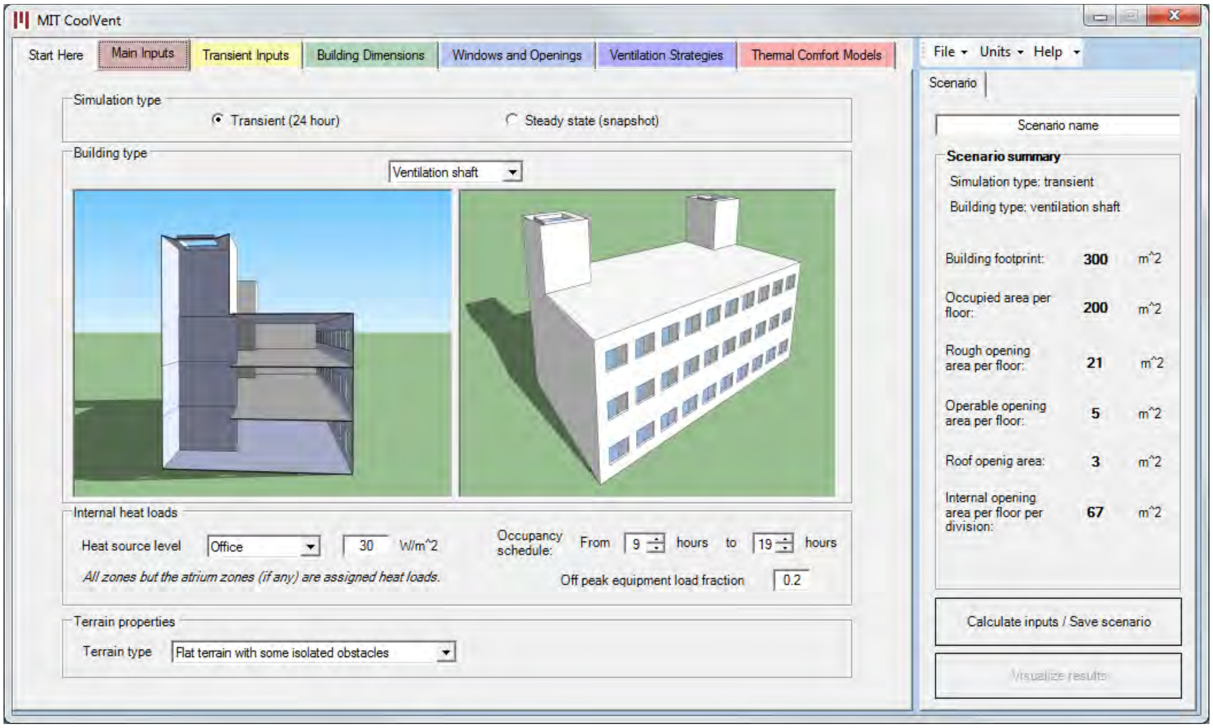



Figure 4: CoolVent interface

## Year 2013

### OBJECTIVES

- To determine the potential of natural ventilation to provide comfortable conditions that will reduce or eliminate the need for air conditioning over the important climatic zones in China and the US
- To promote the widespread application of this technology for energy efficiency and improved indoor climatic conditions

### SUMMARY OF TASKS

*Improvement of CoolVent*

CoolVent was further improved to simulate a new type of building. The new building geometry is common of naturally ventilated offices and involve different flow phenomena not addressed in other building types previously included in CoolVent or other multizone computer programs. The new geometry also allowed us to validate CoolVent against another demonstration building in Japan. This building was designed using, in part, CoolVent, as part of a different project. Nevertheless, inclusion of this building geometry into CoolVent and the validation using experimental data from the actual building were done under the CERC-BEE 1.0 project.

Additional modifications were made to CoolVent to estimate the potential of natural ventilation in the US. CoolVent was modified to be able to estimate energy consumption and to evaluate comfort conditions in each zone of the building. These modifications are all important when establishing the potential of natural ventilation to keep occupants comfortable while reducing the need for air conditioning. Different building types and cities were chosen to be representative of commercial buildings in the US, and simulated using CoolVent under different cooling strategies to estimate energy savings achieved by incorporating natural ventilation.

- Inclusion of an additional building type in CoolVent: ventilation shaft. This geometry was used during the commissioning of a building in downtown Tokyo by MIT researchers
- Integration of CoolVent with MIT Design Advisor Capability to increase simulation and optimization capabilities
- Increased capability of CoolVent to estimate pressure drops along ventilation flow path. Possibility of defining ventilation elements in openings and air paths, such as grates, air path expansion and contraction, dampers. These are all flow path elements present in practically all ventilation systems
- Evaluation of design based both on energy consumption as well as thermal comfort criteria. Thermal comfort criteria include percentage of time under comfort conditions per zone, per floor and per time of the day

*Determine potential of natural ventilation in the US and China*

CoolVent was used to compare energy consumption between different ventilation strategies in different buildings and cities in the United States. The buildings were chosen based on the DOE Commercial Building Benchmark Models, so they are representative of commercial buildings in the US. Ten different cities were selected to represent relevant climate areas in the country (Atlanta, Chicago, Duluth, Fairbanks, Houston, Los Angeles, Miami, Minneapolis, Phoenix and Seattle).

*Monitoring of buildings*

- Began monitoring of building in downtown Tokyo. MIT collaborated on its design and commissioning using CoolVent

*Communication and dissemination*

- Hosted and participated in the IEA annex 62 Ventilation cooling. This program will establish and publish design guidelines for natural ventilation
- Published paper regarding the hybrid ventilation control systems and full scale monitoring of buildings. This paper is related to the work done for the building in Tokyo
- Participated in CISBAT 2013 conference on Cleantech for sustainable buildings. One paper published in the proceedings of this conference

**MAJOR FINDINGS AND OUTCOMES**

- CoolVent used as part of the commissioning of building in downtown Tokyo. Experimental results obtained from monitoring of building will be used to further validate CoolVent
- Results from monitoring of the Artists for Humanity EpiCenter building used to improve performance of night cooling in this building. Recommendations sent to building operators
- Research on natural ventilation potential in the US showed that natural ventilation aided with a ventilation fan can keep a comfortable indoor environment in the cities of Duluth, Fairbanks, Los Angeles and Seattle for close to 100% of the occupied hours. Other findings include, for example, that properly controlling the fan during night cooling in a retail building, can reduce energy consumption by 59% in Atlanta, 36% in Phoenix and up to 71% in Minneapolis. Standalone retail buildings in Chicago and Houston were found to benefit from a hybrid ventilation system as opposed to typical ac systems, with energy savings of 65% and 38%, respectively
- One paper published in peer-reviewed research journal and one paper published in peer-reviewed conference proceedings

Figure 5: Building in Tokyo, Japan. CoolVent was used during the commissioning of this building

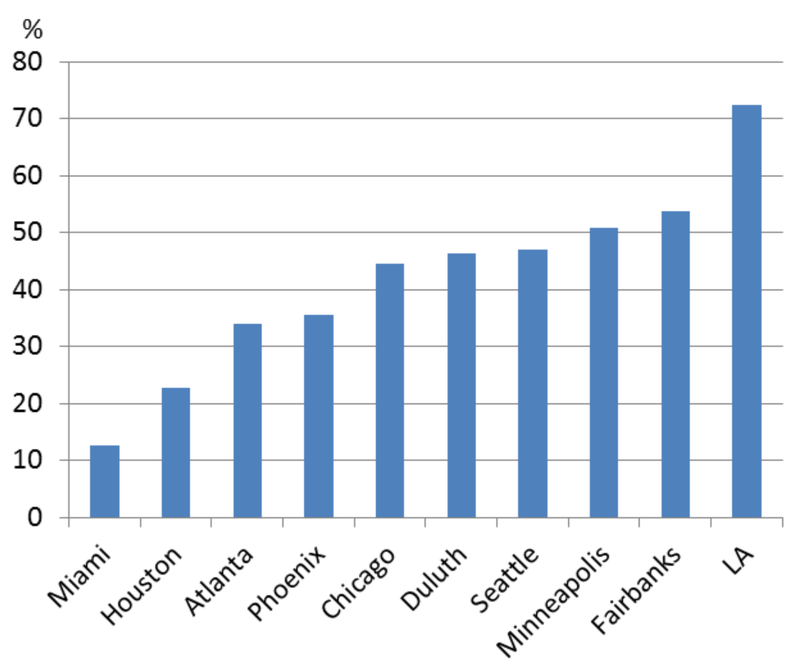



**Figure 6: Results from study to estimate potential of natural ventilation to provide comfort conditions and energy savings in commercial buildings. Chart shows percentage of energy saving of hybrid mechanical-natural mode compared to air conditioning in commercial buildings in different cities in the US in different climate regions. Depending on climate region, energy savings in the US can be between 10 to 70% of consumed energy, demonstrating feasibility of natural ventilation as an effective passive cooling technique.**

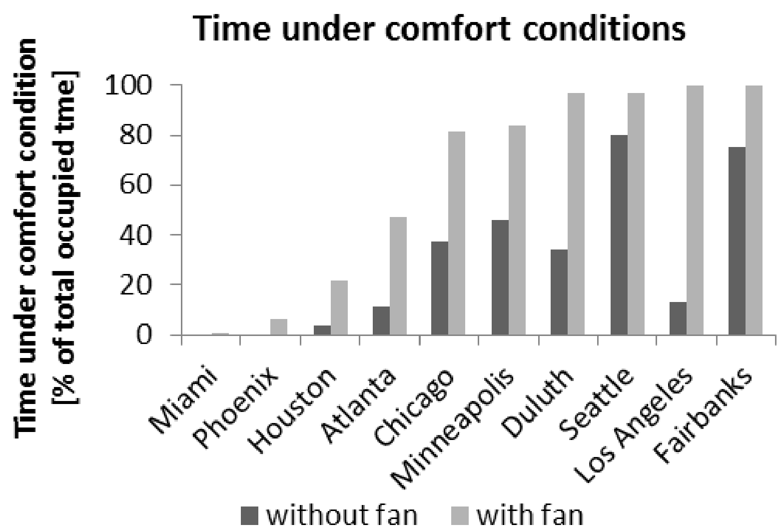



**Figure 7: Results from study to estimate potential of natural ventilation to provide comfort conditions and energy savings in commercial buildings. Chart shows percentage occupied time under comfort conditions in typical commercial buildings in different cities in the US using either natural ventilation or fan-assisted natural ventilation. Fan assisted ventilation is a common strategy to reduce energy consumed for cooling, as a fan consumes a fraction of the energy of a typical AC system.. Depending on weather region, natural ventilation can be used to keep occupants comfortable up to 80% of the time without a fan and 100% of the time including one.**

## Year 2014

**OBJECTIVES**

- To determine the potential of natural ventilation to provide comfortable conditions that will reduce or eliminate the need for air conditioning over the important climatic zones in China and the US
- To promote the widespread application of this technology for energy efficiency and improved indoor climatic conditions

## SUMMARY OF TASKS

### *Improvement of CoolVent*

From the monitoring of demonstration buildings in the US and Japan, we learned that control of hybrid systems is the main challenge faced by building operators to achieve comfort conditions and substantial energy savings in these buildings. For this reason, MIT started developing simple control guidelines for hybrid systems. The guidelines were extracted from a full optimization of a naturally ventilated space with thermal mass.

- Incorporated new control strategies into CoolVent based on dynamic programing optimization of a space with thermal mass. Simple rules of thumb to control a building with hybrid ventilation system were extracted from optimization.

### *Monitoring of buildings*

As part of CERC 1.0 several buildings in China were made available to be used as demonstration for our project. We were in contact with three projects, one of them being The Singyes Green Building in Zhuhai, China. MIT and Chinese colleagues started working on this building, by looking at the potential of natural ventilation in this building. MIT identified a potential problem with the design of the façade in this building. CFD simulations carried out by MIT confirmed this problem. MIT proposed some solutions to this problem. CFD simulation results and suggested solutions were sent to our colleagues in China.

- Started working with Chinese industrial partner (Singyes) in a demonstration building in Zhuhai, China. Academic partner is Tongji University. MIT, Singyes and Tongji met (remotely) to coordinate project effort
- Identified potential problem in façade design of Singyes' building. Sent reports to Singyes with CFD simulation results showing issue and proposed solutions to problem
- Sent report to Singyes showing the potential of natural ventilation to keep the building in Zhuhai under comfortable conditions, as percentage of total occupied time that natural ventilation could be used
- Finished monitoring of building in Tokyo. Results presented in peer-reviewed scientific conference

### *Communication and dissemination*

- Hosted first workshop on natural ventilation at MIT. Main objectives of the workshop is to promote the widespread application of natural ventilation and CoolVent as design tool. Workshops like this have proven to be an effective technique to reach more users of architecture-oriented software
- Participated in IEA annex 62 on ventilative cooling
- Participated in Roomvent 2014 conference. Presented two research papers, which were also published on the proceedings of the conference

## MAJOR FINDINGS AND OUTCOMES

- Started working with Chinese industrial and academic partners, Singyes and Tongji University. MIT identified problem with façade of building that can impact in negative manner the performance of natural ventilation. MIT suggested possible solutions for this problem
- Sent report to Singyes showing the potential of natural ventilation to keep the building in Zhuhai under comfortable conditions, as percentage of total occupied time that natural ventilation could be used
- Finished monitoring of building in Tokyo. Experimental results showed excellent agreement with CoolVent
- Published two papers in peer-reviewed conference on cooling and ventilation

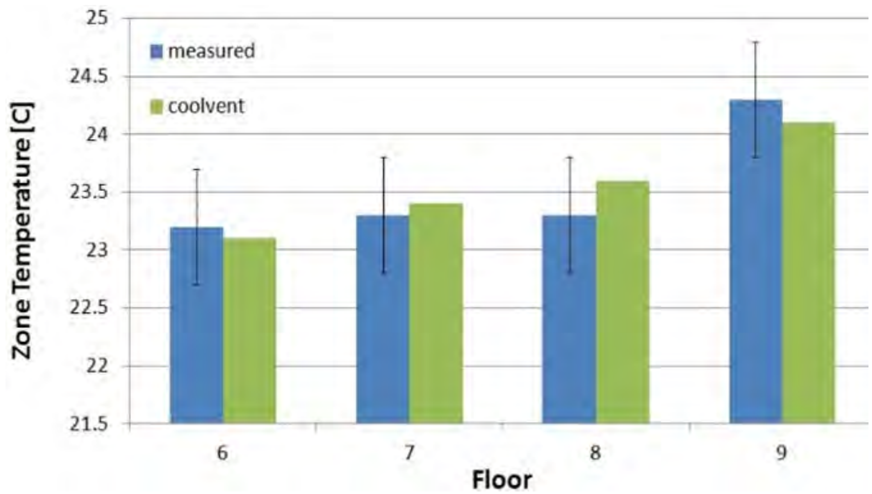



Figure 8: Comparison of CoolVent with measured temperatures in building in Tokyo, Japan.

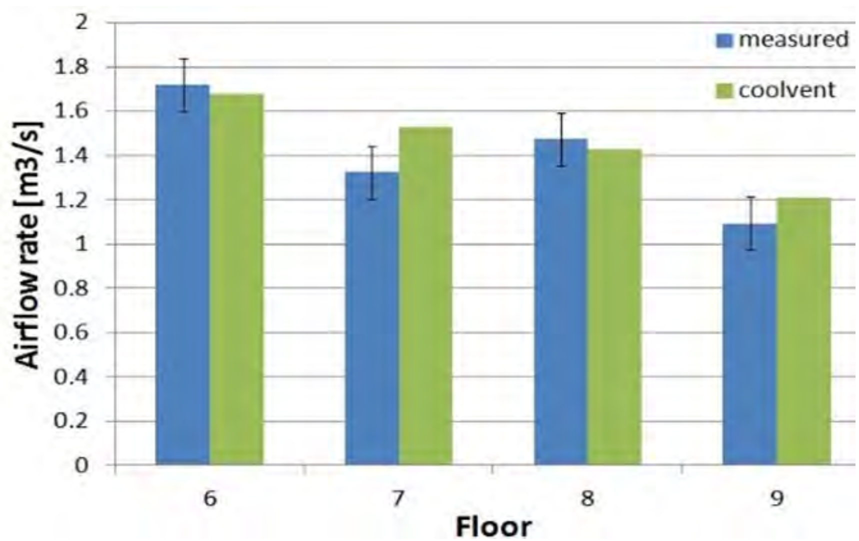



Figure 9: Comparison of CoolVent with measured airflow rates in building in Tokyo, Japan.

## Year 2015

### OBJECTIVES

- To determine the potential of natural ventilation to provide comfortable conditions that will reduce or eliminate the need for air conditioning over the important climatic zones in China and the US
- To promote the widespread application of this technology for energy efficiency and improved indoor climatic conditions

### SUMMARY OF TASKS

*Improvement of CoolVent*

Improvement of CoolVent during this year focused on adding capabilities that no other multizone computer program has, but that are critical to simulate natural ventilation accurately.

- Developed improved model to predict thermal stratification in naturally ventilated buildings. CoolVent is unique in that no other multizone tool can predict thermal stratification. Thermal stratification is needed to accurately predict comfort conditions, and thus ensure that occupants are comfortable
- Developed simple methods to estimate radiative view factors in occupied buildings, extending existing model that is only valid for a space with a single occupant. Method does not require meshing the geometry of the space, making it significantly faster that ray tracing methods. With both view factors and the air thermal stratification model, CoolVent will be capable of estimating operative temperature, an important input in thermal comfort models for mechanical, natural and hybrid ventilation

- Developed method to account for two-way flow between rooms and cold ventilation chimneys. Critical to simulate transient flows in buildings with atria or ventilation shafts. Method to be included in CoolVent

*Monitoring of buildings*

- Defined final geometry of the façade of the demonstration building in Zhuhai, China, to improve performance of natural ventilation in this building
- Defined the overall strategy for the experimental test of the geometry of the façade of the building in China. Sent strategy to Tongji University and Singyes to carry out the experimental measurements

*Communication and dissemination*

- Hosted the IEA Annex 62 conference Ventilative Cooling at MIT on October 12th and 13th, 2015. Researchers from Europe, China and Japan presented work related to natural and hybrid ventilation

**MAJOR FINDINGS AND OUTCOMES**

- MIT work resulted in redesign of façade element in building in Zhuhai, China
- New thermal stratification model to be used in CoolVent. CoolVent is the only multizone model capable of predicting thermal stratification, thus improving thermal comfort predictions
- CoolVent can predict operative temperatures more accurately than currently possible in multizone models

**Figure 10: New façade design in building being built in Zhuhai, China. Work done by MIT, together with Chinese colleagues resulted in the redesign of the façade of this building. New design will improve the performance of natural ventilation in this building.**

## Major Outcomes and Achievements

- MIT is developing a design tool for naturally ventilated buildings that can be used with confidence by designers and architects based on a multizone model of buildings. As part of this project MIT's design tool has been improved. This tool has unique capabilities that no other multizone software has.
- Two naturally ventilated buildings monitored, one in the US and one in Japan. A third one being monitored in Zhuhai, China. Results compared to MIT's design tool show excellent agreement between simulation and monitoring results.
- MIT's design tool used in the commission of building in Tokyo, Japan.
- MIT aided in the design of the façade of a building being built in China. This is a collaboration with industrial and academic partners in China. Currently monitoring this building.
- Five research papers published in peer-reviewed journals and conferences on clean energy and ventilation research in buildings
- New models to predict air thermal stratification and operative temperature in MIT's design tool, vastly improving the accuracy of the prediction of comfort conditions in simulated spaces. In addition, a new method to estimate two-way flow between a space and a cold ventilation shaft. All these capabilities are not available in any other multizone software.

### Standards, Codes, and Policies Influenced

- Design handbook on natural ventilation being written as part of EIA Annex 62 program

### Products Launched

- CoolVent (coolvent.mit.edu)

### Workshops

- Natural Ventilation Workshop at MIT / August 20, 2104 / MIT Campus, Cambridge, MA
- CoolVent Workshop at Harvard University - Graduate School of Design / September 22, 2014 / Harvard University Campus, Cambridge, MA
- CoolVent Workshop for students at the University of California at Berkeley / November 6, 2014 / Remote from MIT Campus, Cambridge, MA

### List of Publications

- FA Dominguez Espinosa, MA Menchaca-Brandan, Stephen Ray, Leon Glicksman. CoolVent, a simple, robust simulation tool for natural ventilation design and analysis. Proceedings of Roomvent 2014, 2014
- Stephen Ray, MA Menchaca-Brandan, FA Dominguez Espinosa, Masashi Fukuda, Leon Glicksman. Measured performance of naturally ventilated commercial building compared to analysis from CoolVent design tool. Proceedings of Roomvent 2014, 2014
- Leon R. Glicksman, FA Dominguez Espinosa, MA Menchaca-Brandan, Stephen Ray, Haofan Cheng. Promoting energy efficiency in commercial buildings by use of natural ventilation. Proceedings of CISBAT 2013, Cleantech for sustainable buildings, 2013
- Menchaca Brandan, M. A., Ray, S, Glicksman, L. Design of Practical Hybrid Ventilation Building in Central Tokyo. ASHRAE Transactions, 118, 2012
- Ray, Stephen D., Menchaca-Brandan, M. A., Glicksman, L. R., Fukuda, M., Hasegawa, I. Overview of Hybrid Ventilation Control System and Full Scale Monitoring. ASHRAE Transactions, 119, 2013

## Collaboration

MIT, Tongji University, and Singyes have been working together to increase the energy efficiency of Singyes' headquarters building in Zhuhai, China. MIT and Tongji University have run Computational Fluid Dynamics (CFD) simulations of the building to analyze the effect of photovoltaic panels located around the façade of the buildings on the performance of natural ventilation. MIT has also studied the potential of natural ventilation to provide comfortable conditions in this building, by measuring the percentage of occupied hours that natural ventilation can be used to keep occupants comfortable. MIT, Tongji University, and Singyes will continue their collaboration regarding the Singyes' building in Zhuhai, China. MIT developed a general plan for experimental work in this building to ensure effective and efficient performance of natural ventilation and its integration with mechanical ventilation. Tongji University and Singyes will run the experiments, which will be analyzed by the Tongji University, Singyes, and MIT. Results from this collaboration have been – and will continue being – documented.

## Conclusions

Natural ventilation is a passive cooling technology that holds promise for significant energy savings, while keeping occupants under comfortable conditions. Natural ventilation can reduce energy consumption between 15% and 70% in commercial buildings, depending on the type of building and climate region where it is located.

CoolVent is a simple, yet accurate tool to help in the design and analysis of naturally ventilated buildings and of buildings with hybrid ventilation systems. It predicts the temperature, airflow and comfort conditions, as well as the energy consumption due to mechanical cooling and heating in each zone of a building. Additionally, CoolVent can be used to test different ventilation strategies including night cooling and fan-assisted ventilation. New models to predict the air thermal stratification, radiative view factors and the two-way flowrate of air during transient simulations have been developed and incorporated into CoolVent as part of the CERC-BEE program. These additions allow the computation and evaluation of comfort conditions in a naturally ventilated space with a higher degree of accuracy and speed than what is possible with previous simulation tools. CoolVent has been validated against experimental measurements of thermal and flow conditions in buildings in the US and Japan. Experimental measurements in a third demonstration building in China will be completed during the summer of 2016. Work in this building has been a collaboration effort between academic and industrial partners in China and the US.

# Building Energy Performance Rating Tools, Database, and Policy Development and Deployment

***Joint Project***

## U.S. Partners

- Lawrence Berkeley National Laboratory
- ICF International
- Johnson Controls, Inc (JCI)

## China Partners

- Ministry of Housing and Urban-Rural Development, Center for Science and Technology of Construction
- China Academy of Building Research
- Tsinghua University

## Overview

Over the past decade, the U.S. Department of Energy (DOE) and U.S. Environmental Protection Agency (EPA) have developed and refined a tool to fairly compare and evaluate the operational energy performance of U.S. commercial buildings. This tool, known as ENERGY STAR Portfolio Manager, has been utilized by more than 400,000 commercial buildings (40% of the U.S. commercial buildings market) and has contributed to cumulative energy cost savings of $3.4 billion and greenhouse gas (GHG) emissions reductions of 17 million metric tons of carbon dioxide equivalent (MtCO2e) through 2014.[2]

While building energy codes and green building labels have existed in China for quite some time, when this project was launched in 2010, there was no parallel tool available in China to equitably evaluate actual operating energy performance of buildings. Given the forecast for significant growth in China's commercial building stock – estimated to increase at five times the rate of the U.S. stock to 18.9 billion square meters by 2050[3] – this project sought to develop a market-oriented, practical system for benchmarking energy performance of Chinese commercial buildings.

## Research Objectives

The objective of this project is to develop a market-oriented, practical system for benchmarking energy performance of commercial buildings (covering at least three building types) in China that will: (1) provide practical processes for buildings in the market to benchmark their energy use and assess their level of efficiency; (2) support comparisons between the energy performance of buildings in the U.S. and China; (3) provide a strong scientific basis for exploring the reasons for differences in the two countries' building stocks; and (4) identify buildings where technology retrofits may be most cost-effective based on anticipated energy savings.

## Major Accomplishments

This project resulted in the development of China's first on-line operational benchmarking tool – the China Building Energy Benchmarking Tool (see Figure 2). The tool evaluates whole-building, operational energy performance relative to peers and normalizes for factors such as weather and occupancy and converts site to source energy for a more equitable comparison of performance. The tool has been integrated into China's Ministry of Housing and Urban-Rural Development (MOHURD) Urban-Scale Building Energy Efficiency and Renewable Energy Project: Energy Performance Benchmarking & Disclosure (EPB&D) in Large Public and Commercial Buildings, which is deploying a national energy performance benchmarking tool and benchmarking and disclosure policy in Beijing and Ningbo from 2015 to 2017, in advance of phased national roll-out, anticipated to begin in 2018. Currently, the China Building Energy Benchmarking Tool is available for offices, hotels, hospitals, and shopping malls at http://115.29.110.113/. In addition to serving as the basis for new national building policies in China, this tool has delivered practical processes for buildings in China to

[2] *ENERGY STAR Facts and Stats* (accessed April 8, 2016); available from https://www.energystar.gov/buildings/about-us/facts-and-stats.

[3] Lixuan Hong, Nan Zhou, David Fridley, Wei Feng and Nina Khanna. "Modeling China's Building Floor-Area Growth and the Implications for Building Materials and Energy Demand." 2014 ACEEE Summer Study on Energy Efficiency in Buildings. Accessed April 8, 2016. Available from http://aceee.org/files/proceedings/2014/data/papers/10-230.pdf.

benchmark their energy use and assess their level of efficiency; identification of Chinese buildings where U.S. technology upgrades are most cost-effective based on anticipated energy savings; opportunities to explore the similarities and differences in the U.S. and China's buildings stocks; and lessons and best practices in building energy management that benefit both the U.S. and China.

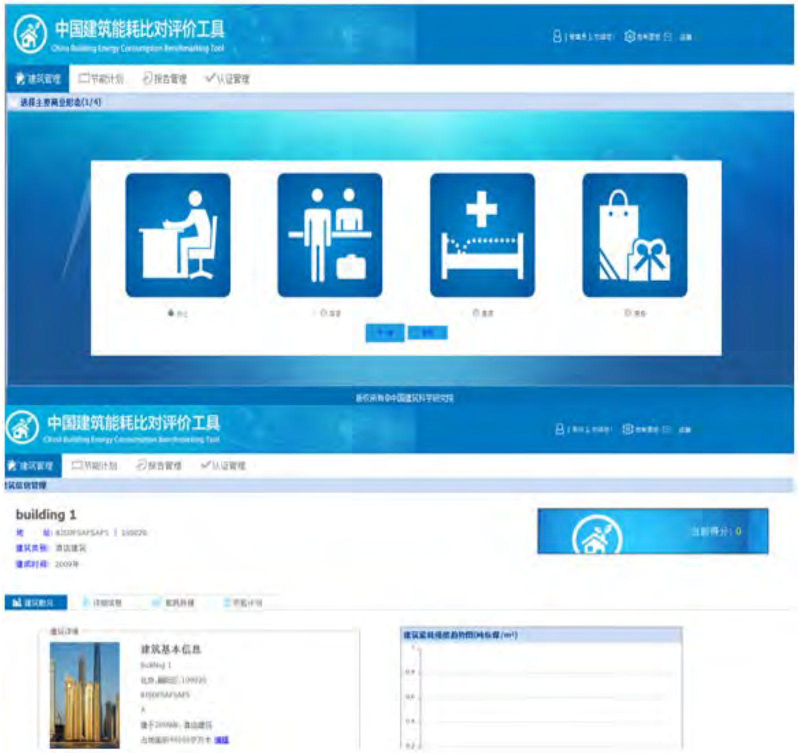



Figure 1: China Building Energy Benchmarking Tool

## Summary of Research Activities

### Year 2011 and 2012

**OBJECTIVE**

- Develop a market-oriented, practical system for benchmarking the energy performance of hotels and commercial offices in China; develop initial understanding of relative energy performance of U.S. and Chinese hotels and offices; and determine the statistically significant operating characteristics that explain the greatest variance in energy usage in Chinese hotels and offices, and make comparisons to U.S. data

**SUMMARY OF TASKS**

- Obtain data required to develop hotel and office benchmarking tools – The team worked in collaboration with the China Tourist Hotel Association (CTHA), Horwath HTL (a multinational hospitality accounting firm), and the China Property Management Institute (CPMI) (a leading national-level property management association) to collect data related to energy usage, costs, and hotel and office attributes that could be used to develop mathematical algorithms for the China hotel and office benchmarking tools.
- Conduct analysis to develop the hotel and office benchmarking tools – The ability of a benchmarking tool to quickly assess and compare a single building to similar buildings in the actual building stock is its notable feature. It does this while normalizing certain characteristics to allow for meaningful comparison. Figure 3 provides an overview of the technical methodology that was used to develop this capability within the China hotel and office benchmarking tools.

- Build an Excel-based prototype benchmarking tool for hotels and commercial offices – Once the key analytic process is complete, the team builds the actual tool interfaces, which are programmed as graphic interfaces using Excel. The Excel tools are similar in function and visual design to online tools.
- Build on-line hotel and office benchmarking tools – Following completion of the Excel-based hotel benchmarking tool, China Academy of Building Research's (CABR) web development team developed a web-page to host the tools and posted the benchmarking tool to the CABR website. The web page is intended to be user-friendly to encourage hotel and commercial office owners or operators, without support from an energy specialist, to use the benchmarking tools to assess energy performance.
- Conduct analysis to develop initial understanding of relative energy performance of U.S. and Chinese hotels and commercial offices.
- Determine the statistically significant operating characteristics that explain the greatest variance in energy usage in Chinese hotels and commercial offices, and compare to U.S. data.

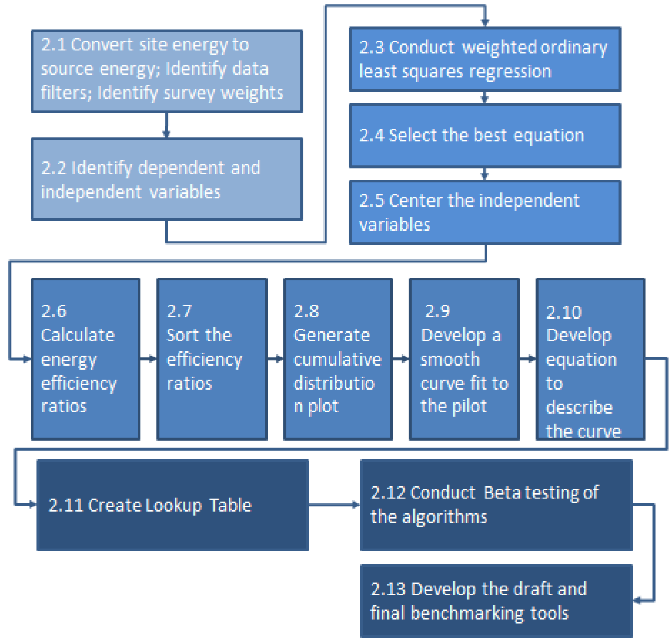



**Figure 2: Technical Methodology for China Building Energy Benchmarking Tool Development**

## MAJOR FINDINGS AND OUTCOMES

### *Identified Refreshable Energy Data Sources for Hotels and Partnerships to Support Commercial Office Energy Data Collection*

A key outcome of the project has been the identification of a refreshable data source for hotels to support development and revisions to the on-line hotel benchmarking tool. Since 2009, ICF has partnered with Horwath HTL (recently acquired by FINDEX, a financial advisory and accounting firm) and China Tourist Hotel Association (CTHA) to conduct an annual "Energy Benchmark Survey" as part of the annual China Hotel Industry Survey. The survey collects annual energy consumption and cost data, as well as hotel attribute data required to develop benchmarking algorithms, for approximately 800 hotels annually. CTHA and FINDEX will continue to run this annual "Energy Benchmark Survey" and share results with CABR and LBNL to support refinements to the hotel benchmarking tool and research on hotel energy performance in China.

For the commercial office sector, while an annual data survey was not developed, Chinese partners CABR and CSTC provided access to refreshable data sources that could be made available to the CERC program in the future. CSTC, China's leading national body for data collection and analysis, has indicated strong support for the development and application of comparative building benchmarking tools and indicated a desire to work collaboratively to develop a national data collection system to support further development and enhancement of these tools in China in the second phase of the CERC program. Through its technical support for the Beijing and Ningbo online data collection platforms (under the MOHURD Urban-Scale Building Energy Efficiency and Renewable Energy Project: Energy Performance Benchmarking & Disclosure in Large Public and Commercial Buildings), CABR can readily access data for hundreds of buildings in Beijing and Ningbo to support building benchmarking tool enhancement efforts. China Property Management Institute (CPMI) has also shown interest and support in data collection for commercial office buildings. In 2011, the CPMI teamed with the CERC program to assist in commercial office building data collection to support development of a commercial office benchmarking tool. As the leading national-level property management association in China with association chapters in more than 90 cities across China, they would be a strong channel partner for collecting data to support development of a national commercial office building energy database.

### *Developed the Prototype On-line Building Energy Benchmarking Tool for China*

In 2012, the CERC program developed a prototype on-line comparative energy benchmarking tool (Figure 4) for the hotel sector in China (this tool has since been upgraded to benchmark hotels, commercial offices, hospitals, and shopping malls and is available at: http://115.29.110.113/.) The prototype tool rated hotel energy performance on a scale of 1 to 100, where 50 is average performance, and automatically normalized for factors such as climate, weather, size, number of workers on main shift, number of commercial refrigeration units, and presence of commercial cooking facilities – the predictive factors of a hotel's energy consumption as determined by regression analysis for more than 700 Chinese hotels – so that hotels' energy performance is compared on a level playing field. As of September 2012, the prototype had been beta tested with data for more than 100 hotels to ensure that the tool was generation uniform rating distributions between 1 and 100 for sample hotels. Test results showed the expected distribution.

**Figure 3: Prototype On-line Hotel Benchmarking Tool for China (no longer web-accessible)**

*Developed Initial Understanding of Relative Energy Performance of U.S. and Chinese Hotels and Offices*

Buildings in the U.S. have high efficiency and also high consumption. There are many large power devices, such as chillers, ventilation fans, and lights, operating full time and in full space, even if only a few people occupy the building. Buildings are typically fully automatically controlled and try to keep the indoor environment constant throughout the whole year, which causes high consumption, including much offset of cold and heat. Thus, although the mechanical efficiency is high, the U.S. buildings still consume double or triple the energy that Chinese buildings do. However Chinese buildings also have many disadvantages. Chinese buildings are used to operating in part-time and part-space, which decreases the energy consumption substantially. But low device and system efficiency is quite common in Chinese buildings. In the case study hotel (RC), the low efficiency of the domestic hot water system in the villa residences and the low efficiency of the pump in waterscapes are discussed deeply. Such phenomenon is common in HVAC and lighting system in Chinese buildings, which should be paid attention to.

By comparing hotels' energy consumption in both the U.S. and China, the common factors that influence building energy use are discussed, and the different drivers are also analyzed. The energy conservation tracks for U.S. and China are as different as the key energy drivers. The main task for Chinese buildings is to increase mechanical and system efficiency, while for U.S. buildings, reducing energy consumption is more significant.

*Key variables that explain energy consumption in Chinese hotel and commercial office buildings and how those compare to key explanatory variables in the U.S.*

In developing the hotel and office benchmarking tools, the team identified the key factors that explain energy consumption in Chinese hotels and offices – which are the key factors that must be normalized in order to fairly compare energy performance. These variables were determined by performing linear regressions on the office data to examine operating characteristics, which might influence office energy consumption. The team evaluated these equations using multiple statistical tests including residual plots, model R2, and individual coefficient significance levels. Based on results of regression analysis, the variables shown below were determined to be statistically significant drivers of energy consumption in Chinese hotels:

5-star (explains 78.3% of variation):
x1: Number of walk-in refrigeration units
x2: Number of rooms per 1000m2
x3: Number of workers per 1000m2
x4: HDD (Heating Degree Days)
x5: CDD (Cooling Degree Days)

4-star (explains 66% of variation):
x1: Number of workers per 1000m2
x2: HDD (Heating Degree Days)
x3: CDD (Cooling Degree Days)
x4: Number of walk-in refrigeration units

3-star (explains 78% of the variation):
x1: gross floor area (sm)
x2: Number of walk-in refrigeration units
x3: CDD (Cooling Degree Days)
x4: HDD (Heating Degree Days)
x5: Number of workers on main shift

These factors are similar to those identified in the U.S. as key explanatory variables that can be used to estimate the expected average source EUI in a hotel. These variables are as follows:

- Number of lodging rooms per 1,000 square feet
- Natural log of the number of workers per 1,000 square feet
- Presence of a commercial food preparation area (yes/no)
- Number of commercial refrigeration units (walk-in, open, and closed) per 1,000 square feet
- Heating degree days times Percent of the building that is heated
- Cooling degree days times Percent of the building that is cooled

A key similarity worth noting, is that in neither the Chinese regression equations nor the U.S. regression equations, was hotel occupancy determined to be an explanatory variable for hotel source EUI or source EU. Further analysis must be conducted to determine why this is the case. It may be that hotels in China and the U.S. are operated to certain comfort conditions, which require a constant energy load, regardless of occupancy rates – thus, overall, the level of occupancy is not a statistically significant predictor of a hotel's energy consumption.

Based on results of regression analysis, the following variables were determined to be statistically significant drivers of energy consumption in Chinese offices:

- x1: CDD (Cooling Degree Days)
- x2: Building Annual Operation Hours (hour)
- x3: Number of Staffs (person)
- x4: Floor Area of Heated/Cooled (SM)

Based on the regression analysis conducted in the U.S., the following six characteristics were identified as key explanatory variables that can be used to estimate the expected average source EUI in U.S. offices:

- Natural log of gross square foot
- Number of personal computers (PCs) per 1,000 square feet
- Natural log of weekly operating hours
- Natural log of the number of workers per 1,000 square feet
- Heating degree days times Percent of the building that is heated
- Cooling degree days times Percent of the building that is cooled

It is noteworthy that the key predictive factors of office energy consumption in China, which were used to develop the office benchmarking algorithms, include only four variables. This is likely due to a small sample size (57 offices).

## Year 2013

**OBJECTIVE**

- Conduct an assessment of the major technical measures for energy efficiency and suggestions for design and operations and maintenance (O&M) of low-energy buildings

**SUMMARY OF TASKS**

- Obtain Chinese Hotel Energy Performance and Characteristics Data – The initial phase of the research project was to develop a database of approximately 100 hotels on which to conduct analysis to identify the key construction, equipment, EE technology, and O&M characteristics of Chinese hotels. This involved, first, developing a comprehensive survey to obtain the required data. Once the survey questionnaire was designed, CSTC conducted the survey with approximately 100 hotels in China. In total, 85 hotels responded to the survey, including 33 in Beijing, 47 in Changzhou, and one each in Fuzhou, Hangzhou, Shanghai, Suzhou, and Xiamen. Of these, 41 were 5-star hotels, 28 were 4-star, and 16 were 3-star or budget hotels. Figure 5 shows hotel survey respondents by city location, climate zone, and star level.

- Conduct Benchmark Analysis – After completing data collection, the team segregated the population of hotels into four quartiles based on energy performance, and determine the construction, equipment, EE technology, and O&M characteristics of each performance category of hotel. To do this, the team utilized the China hotel energy performance benchmarking tool, which was developed under the CERC program. Utilizing this tool, the ICF team benchmarked the energy performance of each of the 85 hotels surveyed and determined its benchmark score (1 to 100). The team then grouped the hotels into four performance quartiles, based on the benchmark score. The lower quartile was composed of hotels that earned a score below 25 (indicating energy performance in the lowest 25% of the population); the second quartile was composed of hotels that earned a score of 25 to 49 (indicating energy performance below the national average, but above the 25th percentile); the third quartile was composed of hotels that earned a score of 50 to 74 (indicating energy performance above the national average, but below the 75th percentile); and the upper quartile was composed of hotels with scores between 75 and 100 (indicating performance better than 75% of the population).
- Determine Characteristics of Each Performance Category of Hotels Surveyed – Following the grouping of hotels into four quartiles based on energy performance benchmark score, the team identified the construction, equipment, EE technology, and O&M characteristics of best and worst energy performing hotels based on survey responses. It did this by reviewing each question of the survey and, for each category of hotel, determining the percentage of respondents providing a particular answer.

Figure 4: China Hotel – Best-Practice Technology and O&M Survey Respondents

## MAJOR FINDINGS AND OUTCOMES

*China Building Energy Benchmarking Tool Functioning as Intended*

Based on the data and analysis of the hotels that participated in the survey, the China hotel energy performance benchmarking tool appears to be functioning as intended. Support for this is found in the fact that hotels that earn the highest energy benchmark scores also, in general, have lower EUIs, as shown by Figure 6. Also, the energy performance of hotels earning a score between 75 and 100 (performance in the top 25% of the market) is demonstrably better than the average performance for hotels in China: specifically, the average source EUI of the hotels earning a score of 75 or above is 59% lower than the national average source EUI for Chinese hotels.

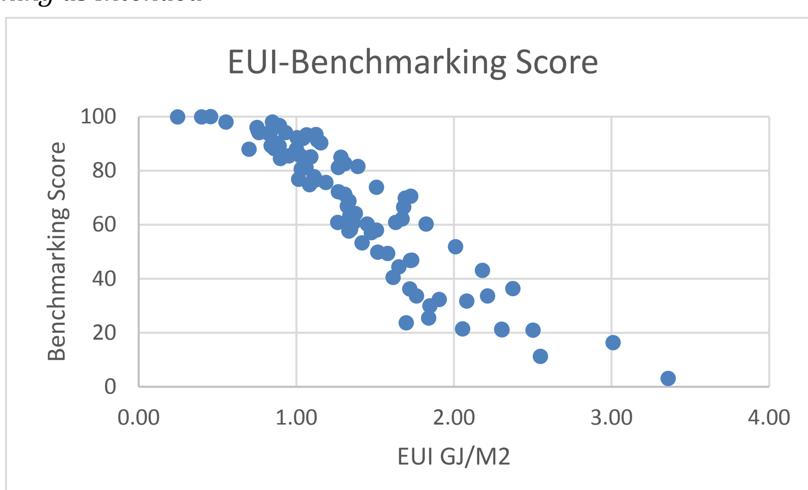


Figure 5: Negative Correlation Between Chinese Hotel Energy Use Intensity and Benchmark Score

Further, based on an analysis of top and poor energy performing hotels, no one clear path to top energy performance in hotels appears to exist but certain characteristics, such as concrete envelope and operable windows – may offer better levels of energy efficiency and energy conservation. Likewise, utilization of the most energy-efficient lamps on the market (low and high pressure sodium and metal halides) and best-practice energy-efficient HVAC equipment/systems, such as district steam, split AC/VRV systems, and renewable energy source heat pumps, can support above-average and top energy performance in hotels. Likewise, while both top and poor energy performing hotels utilize EE technologies, top performing hotels were more likely to manually control HVAC equipment and to have invested in an outside audits or energy retrofit in the past three years, suggesting that owner and management commitment, and careful O&M, play an important role in the energy performance in Chinese hotels. Further, certain construction characteristics, such as glass envelope and direct combustion lithium bromide absorption chillers (natural gas) should be avoided if high levels of energy performance are to be achieved.

A full summary of outcomes is available in "Construction, Equipment, Technology, and Operational Characteristics of Very Low-Energy Hotels in China," Paper Collection for the Tenth International Conference on Green and Energy-Efficient Buildings (March 2014): 1-15.

## Year 2014

**OBJECTIVE**

- Provide DOE with information on Chinese innovations in real-time, on-line building energy monitoring, as well as emerging policies associated with energy performance benchmarking and disclosure and emissions trading for the commercial buildings sector, and to provide preliminary recommendations for leveraging these initiatives to improve the performance of the U.S. building stock

**SUMMARY OF TASKS**

- The project research was carried out over a twelve-month period (March 2014 to February 2015). Research findings draw on both primary and secondary sources of information. Specifically, the data collection methods that were utilized for this project included desk research and stakeholder consultation, as described in the sections that follow.
- A variety of reports, presentations, and websites associated with CERC BEE, Annex 53, U.S. DOE's Energy Information System, Tsinghua's Building Energy Research Center, and Chinese building energy policies were obtained. Materials were reviewed by team-members and relevant information was extracted and input into this report.
- In addition to desk research, stakeholders completed questionnaires, interviews, and group discussion to provide the latest information on building energy monitoring systems and policies in China. Representatives from four stakeholder groups were interviewed or engaged in discussion: MOHURD CSTC, CABR, Tsinghua University, and LBNL

**MAJOR FINDINGS AND OUTCOMES**

A full summary of the research findings is available in the "Building Energy Policy Memo" submitted to DOE in March 2015.

- Lesson learned 1: MOHURD's national on-line, real-time building energy monitoring platform has failed to deliver large, comprehensive, and accurate building energy database for analysis.
- Recommendation 1: U.S. DOE should learn from the failure of MOHURD's national real-time, on-line building energy monitoring platform. A national system modeled after China will not enhance the efficiency and reliability of large-scale, national data collection efforts.

According to MOHURD CSTC and Tsinghua University, MOHURD's national on-line, real-time building energy monitoring platform has failed to deliver large-scale, comprehensive, and accurate building energy data sets that can be analyzed and inform new building energy policies, standards, and codes. MOHURD CSTC expressed deep disappointment with its national on-line, real-time monitoring system, which intends to collect real-time building energy data for thousands of buildings. CSTC said that the data is full of holes (due to broken sensors, sub-meters, and insufficient recording of data sources) and is of very little use to MOHURD. According to Tsinghua, which is periodically invited by MOHURD to review its data sets, analysis of data is impossible since there are numerous missing data points and very little information on where data is coming from (i.e., which buildings and meters). The only portion of the data that is typically useful for analysis is the energy consumption data. Tsinghua has said that they have not yet been able to meet MOHURD's request for analysis because the data quality is so poor. Given DOE's goals of improving the reliability and efficiency of its national building energy data collection efforts, and the poor results from MOHURD's application of real-time, on-line monitoring systems, it is not advised that, at this time, this format be employed for capturing data to support U.S. national database development.

- Lesson learned 2: Tsinghua's small-scale, real-time, on-line monitoring platform has been an effective tool for conducting research and analysis on building energy performance in China, which has contributed to new building energy codes, standards, and policies.
- Recommendation 2: DOE should continue to engage in collaborative research efforts with China that employ small-scale, real-time, on-line monitoring systems to conduct research and analysis on building energy performance.

While large-scale efforts to collect and analyze data utilizing real-time, on-line monitoring systems have been disappointing in China, small-scale efforts to collect and analyze data using on-line monitoring systems have proven valuable. These small-scale efforts have typically been led by universities (i.e., Tsinghua University or Tongji University) or local building research institutes (i.e., Shenzhen Building Research Institute and Shanghai Building Research Institute). They focus on better understanding the drivers of top energy performance in Chinese buildings, thereby supporting policy developments (i.e., codes and standards, energy-efficient building labeling programs, equipment retrofit programs).

The U.S. DOE should continue to engage in collaborative research efforts with China that leverage small-scale, real-time, on-line monitoring systems to conduct research and analysis that will lead to better building energy performance in the U.S. An example of such as project is the CERC BEE 2011-2012 project, whereby DOE funded LBNL and ORNL to engage in collaborative research with Tsinghua University to develop an international standard methodology for building energy data collection, presentation, and analysis; apply the methodology to typical energy monitoring platforms in the U.S. and China; and compile real-time data from U.S. and Chinese buildings. The research led to a better understanding of the driving forces behind discrepancies in U.S. and Chinese building energy performance; identification of gaps in current building energy monitoring, data collection, and analyses; and new international tools to collect and analyze quality energy data to provide to stakeholders. These types of initiatives that leverage small-scale, on-line monitoring platforms, led by universities and research institutes, will have the most direct benefit for U.S. stakeholders since they can be tailored more specifically to the interests of the U.S. and avoid problems associated with data quality.

- Lesson learned 3: China's city-level, on-line monitoring platforms, particularly in the cities of Shanghai, Shenzhen, and Beijing, are delivering accurate, reliable, granular data and playing key roles in innovative ETS and EPB&PD policies to rapidly improve the energy performance of China's building stock.
- Recommendation 3: DOE should peer match Chinese cities at the forefront of on-line data collection, monitoring, and EPB&PD (e.g., Beijing, Shanghai, and Shenzhen) to U.S. cities implementing EPB&PD programs and leveraging SEED in order to gather lessons from China in order to improve technical data collection, analysis, and identification of retrofit/operational opportunities in the U.S. building stock.

While China's national real-time, on-line monitoring platform has not delivered the intended results, many of its city-level monitoring systems are consistently providing timely, reliable, accurate, and granular building energy performance data to city governments.

These platforms are playing a key role in improving the energy performance of the Chinese building stock through verification of compliance with building codes; identification of buildings for audits and retrofits; monitoring the energy savings of retrofitted buildings; and identifying buildings for green building certification and monitoring the performance of green buildings.

Furthermore, China is moving rapidly to develop a national-level building energy performance platform and tool, which will allow buildings connected to the city-level, on-line monitoring systems to benchmark their performance against peers, along with EPB&PD policies that will spur use of the benchmarking tools to improve building performance. Given parallel efforts in numerous U.S. cities on EPB&PD (New York, Washington, DC, Seattle, and San Francisco), China can offer technical and policy lessons to U.S. cities engaged in EPB&PD efforts. Specific focus should be placed on China's unique city-level, on-line monitoring capabilities to see if similar systems could be developed in the U.S. that would allow for rapid, accurate, reliable data collection, monitoring, and benchmarking for city-level buildings.

- Lesson learned 4: China's ETS is motivating building owners and managers in China to cut their energy consumption and carbon emissions.
- Recommendation 3: DOE should continue to monitor the progress of China's ETS pilots and forthcoming national ETS to understand its impact on building sector energy performance. DOE should consider gathering lessons from the

China ETS and encouraging U.S. regional ETS (Regional Greenhouse Gas Initiative (RGGI) and Western Climate Initiative, to apply successful techniques from China to improve the energy performance of the US building stock.

Through both sticks and carrots, the fledgling China ETS pilot programs in Beijing and Shanghai are successfully improving the energy performance of the building stock. In both Beijing and Shanghai, companies are being spurred by new ETS policies to curb energy consumption and GHG emissions. Some companies are taking initiative to leverage government subsidies to cut energy consumption and selling excess emissions credits on the local exchanges. Other companies are being compelled to action due to penalties and pressure from failure to comply. Regardless, ETS pilots are providing an incentive for buildings to improve energy performance and cut carbon emissions.

DOE should continue to monitor the progress of China's ETS pilots and forthcoming national ETS to continue to understand its impact on building sector energy performance. Where policies are proving effective, DOE should encourage US regional ETS (RGGI and the Western Climate Initiative) to follow suit. While RRGI accepts carbon credits from the reduction or avoidance of CO2 emissions from natural gas, oil, or propane end use combustion due to end-use energy efficiency in the building sector, the primary focus of each program is fossil fuel electric generation units and large industrial fa¬cilities. China's experience linking ETS to the buildings sector could provide opportunities for expansion of U.S. efforts into this sector.

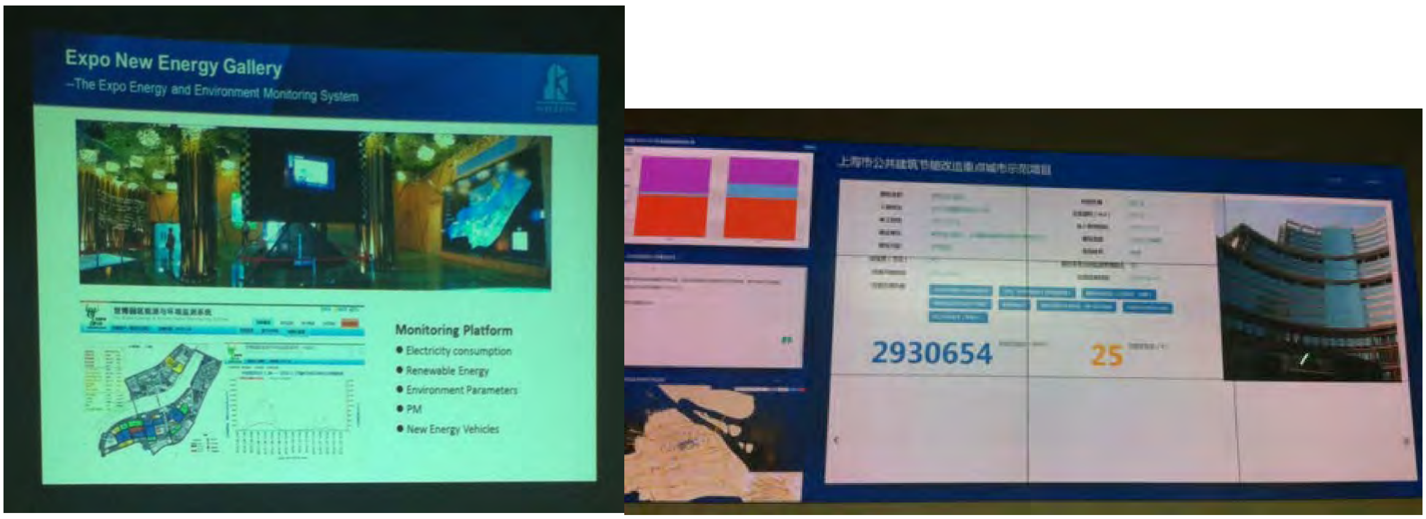



Figure 6: (Left) Shanghai EUMP Display Expo New Gallery Building. (Right) Shanghai EUMP Display Shanghai Commercial Office Building

## Year 2015

### OBJECTIVE

- The objective of this research is to evaluate the China Building Energy Benchmarking Tool (an operational benchmarking tool) developed under CERC 1.0 alongside two additional building analytic tools – the DOE Asset Score, and Johnson Controls' (JCI) LEAN Energy Analysis – in terms of overall capacity to motivate investment and/or improvements in BEE in China, and based on this evaluation, to identify lessons learned and offer recommendations for enhancements to the China Building Energy Benchmarking Tool and/or development of new analytic tools under CERC BEE 2.0 that will increase adoption of new clean energy technologies in China

### SUMMARY OF TASKS

- The project research was carried out over a twelve-month period (March 2015 to February 2016). The approach included reviewing analytical tools, identifying a target population, testing analytical tools, and obtaining feedback on tool results

### MAJOR FINDINGS AND OUTCOMES

The LEAN Energy Analysis provides the best "bang for the buck" of the analytical tools tested. It requires very minimal data inputs, just monthly energy data for 2-3 years, as well as the building location and floor area. With those minimal inputs, it provides building operators with information that they need to take next steps toward energy performance improvements: recommended energy efficiency upgrades and potential energy and cost savings. The outputs were considered to be practical, informative, and very valuable for financial decision makers.

The LEAN Energy Analysis is not intended to replace the China Building Energy Benchmarking Tool. The benchmarking tool provides a simple performance metric that is easy for building operators to understand, and normalizes for building operation to assess performance relative to peers. LEAN does not provide the same normalization, or the simple performance metric. However, the benchmarking tool does not provide guidance on next steps after benchmarking, so the LEAN Energy Analysis can be used as a complement to the benchmarking tool. It dives a step deeper to assess the weather sensitivity of the building's performance, and can be used as a precursor to an energy audit. If a building receives a benchmarking score of 30, the LEAN Energy Analysis can be used to determine that the building base load and heating load is low, but the cooling load is extremely high, and the tool will provide recommendations that are focused on improving the cooling load. A building operator may be able to directly implement some simple operations and maintenance recommendations, such as adjusting temperature set-points. The tool can also help a building operator work with an energy service provider to investigate more complex recommendations.

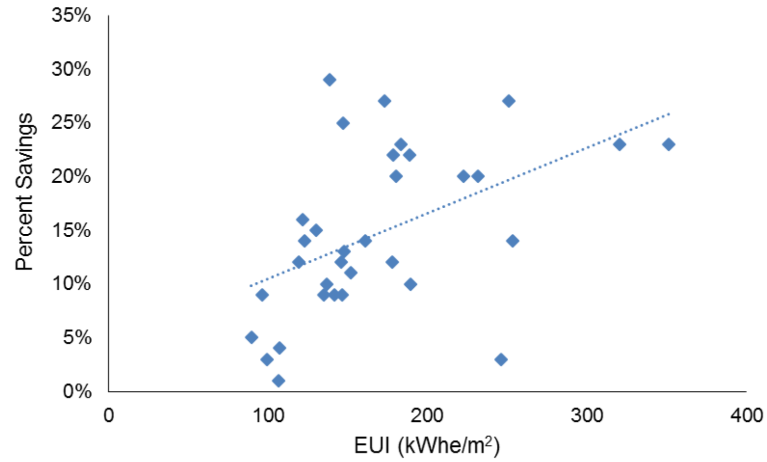


Figure 7: LEAN Energy Analysis Tool: Savings vs. EUI

In Figure 7, results are presented for the LEAN Energy Analysis tool for all hotel properties. The trend line in this graph shows that potential savings are higher for properties with higher energy use intensity, which is to be expected. There is scatter around the trend line in this graph as well. The savings potential is not simply proportional to the total energy intensity of the property, but rather is dependent on the response of the building to weather.

The Asset Score also provided energy savings recommendations. These recommendations were considered helpful, but overall the tool was considered less valuable than the LEAN Energy Analysis. The tool requires more complex data inputs. These inputs are not all readily available in the China market, making the tool impractical for routine use. Additionally, the tool is based on modeled data. While the recommendations themselves are valuable, the savings estimates generated by the tool do not represent the actual energy savings that would be achieved by the building. As a result, investment in this type of tool is not recommended at this time. It is considered premature for the China market.

A full summary of the research findings is available in the "Building Energy Benchmarking Policy Memo" submitted to DOE in March 2016.

## Major Outcomes and Achievements

### Standards, Codes, and Policies Influenced

- In 2012, the Beijing Construction Commission set an objective for its 12th Five-year Plan to develop online benchmark tools.
- In 2014, the China Building Energy Benchmarking Tool developed under CERC 1.0 was adopted by the Ministry of Housing and Urban-Rural Development (MOHURD) as the model benchmarking tool for its Urban-Scale Building Energy Efficiency and Renewable Energy Project: Energy Performance Benchmarking & Disclosure in Large Public and Commercial Buildings (2014-2017), whereby MOHURD is developing a national building energy performance benchmarking methodology and tool and preparing guidelines for energy performance benchmarking and disclosure for large public and commercial buildings at the national level and city level. MOHURD is currently carrying out energy performance benchmarking and disclosure pilot activities in Beijing and Ningbo, in advance of phased national program rollout, anticipated to begin in 2018.

### Products Launched

- China Building Energy Benchmarking Tool for commercial offices, hotels, hospitals, and shopping malls, available on-line at: [http://115.29.110.113/](http://115.29.110.113/).

### Workshops

- At the Asia Hotel Forum (AHF) in Shanghai in September 2012, China Academy of Building Research presented findings from the "2011 Annul China Hotel Energy Benchmarking Survey" and launched the China Hotel Benchmarking Tool development effort under CERC to more than 500 representatives from the Chinese hotel industry.
- In collaboration with the International Partnership for Energy Efficiency Cooperation (IPEEC), hosted workshop on "Building Energy Rating Schemes: Issues and Prospects." Speakers included representatives from MOHURD, Center for Science and Technology of Construction, China Academy of Building Research, Sustainable Energy Partnerships, ICF International, Shanghai Building Research Institute, and Jiangsu Province (October 2013, Beijing).
- Trained JCI and Lutron sales staff on use of the China Building Energy Benchmarking Tool to sell U.S. technologies and services in China (March 2015, Beijing).
- JCI's Manager in the Service & Energy Efficiency Department, Beijing and Member of the U.S.-China Energy Cooperation Program (ECP) participated in the Paulson Institute and the China Center for International Economic Exchanges (CCIEE) Building Energy Benchmarking and Disclosure Dialogue on June 9th in Beijing. At the event, JCI shared with policymakers how it is utilizing the China Building Energy Benchmarking Tool to advance the sale of JCI building energy efficiency equipment and services, thereby benefitting employees and customers.

### List of Publications

- Carolyn Szum, Zhao Yanbing, Zhou Zhou, Hao Bin, and Liu Shan, "Construction, Equipment, Technology, and Operational Characteristics of Very Low-Energy Hotels in China," Paper Collection for the Tenth International Conference on Green and Energy-Efficient Buildings (March 2014): 1-15

## Collaboration

The LBNL team partnered with JCI to apply JCI's LEAN Energy Analysis on 36 Chinese hotels, 2 commercial offices, and 1 shopping mall to determine the tool's effectiveness (vis-à-vis the China Building Energy Benchmarking Tool and the DOE Asset Score) in terms of overall capacity to motivate investment and/or improvements in BEE in China. Based on a comparative analysis, JCI's LEAN Tool demonstrated superior performance.

JCI's involvement made possible the evaluation their LEAN Energy Analysis as a method/tool for motivating investment and/or improvements in BEE in China. This tool provides unique advantages in terms of its reliance on actual building energy consumption data (as opposed to simulation), and its specific capacity to identify energy improvement opportunities in buildings with low energy use intensity (EUI) (which is the case for many Chinese buildings as compared to U.S. buildings).

Lessons learned: industry involvement and commitment has been essential in delivering a successful, market-tested benchmarking tool to China. Senior management (i.e., C-level) support at JCI has allowed for seamless collaboration between industry and research institutes.

This research project was carried out by a consortia of organizations: LBNL, ICF, MOHURD CSTC, Tsinghua University, and CABR from 2011 to 2015 under CERC BEE 1.0, and resulted in the development of China's first on-line Building Energy Benchmarking Tool for commercial offices, hotels, shopping malls, and hospitals. Work was carried out through regular conference calls and working group meetings (approximately monthly from 2011 to 2015).

Involvement of Chinese government, university, and research institutes was critical in successfully acquiring data to support benchmarking tool development and achieving critical policy impacts, such as the Beijing Construction Commission's inclusion of the development of on-line benchmarking tools in its 12th Five Year Plan. MOHURD's effort to include mention of benchmarking in China's 13th Five Year Plan, and MOHURD's launch of its Urban-Scale Building Energy Efficiency and Renewable Energy Project: Energy Performance Benchmarking & Disclosure in Large Public and Commercial Buildings (2014-2017), whereby it is developing a national building energy performance benchmarking methodology and tool based on the CERC model.

Lessons learned: regular communication is essential to success. Monthly in-person meetings helped the team work together in a truly collaborative fashion to deliver a Chinese on-line benchmarking tool and carryout associated research.

## Conclusions

The China Building Energy Benchmarking Tool developed under CERC 1.0 is the first of its kind in China and allows policymakers and market actors to perform whole building energy performance comparison and analysis based on actual energy usage for the hotel, office, hospital, and retail sectors. Indicative of the project's overall success, MOHURD has adopted the CERC 1.0 benchmarking tool as the model for its Urban-Scale Building Energy Efficiency and Renewable Energy Project: Energy Performance Benchmarking & Disclosure in Large Public and Commercial Buildings (2014-2017). In addition to serving as the basis for new national building policies in China, this tool is helping to build a stronger market for energy efficiency technologies and services, including U.S. technologies. JCI, a company at the forefront of building energy benchmarking in North America and China, has introduced the tool to their active clients who own and manage commercial buildings, inspiring their clients to regularly collect energy data and gain a deeper understanding of the energy performance of their properties. JCI has found that the China Building Energy Benchmarking Tool provides an authoritative and fair way to help their clients understand the energy consumption challenges associated with their properties, and to help them address these challenge. Building off this success, JCI will partner with LBNL, ICF, CABR, and MOHURD under CERC 2.0 to expand on the China Building Energy Benchmarking Tool to incorporate "pre-audit" capabilities, which specify likely technology and equipment upgrade opportunities, and associated energy and cost savings.