Building Energy Smart Technologies (BEST) Center

Spring 2025 Industry Advisory Board Meeting
April 24-25, 2024

Welcome from the Leadership Team

Thank you for attending the BEST Center's Spring 2025 Industry Advisory Board (IAB) Meeting. We hope you enjoy the discussions with colleagues, proposal presentations, and updates from ongoing research projects from our research project teams. The morning session will start with a welcome and keynote from Luiz Fernando Huet de Bacellar, VP of Engineering & Technology at Eaton on the future of DC-powered buildings, followed by presentations of proposals being considered for funding in the next funding year (FY25-26). After lunch, FY24-25 research projects will be presented by students and faculty. The afternoon presentations will be followed by a lightning poster session, giving attendees a chance to connect one-on-one with our student researchers. We will wrap up in closed session with our IAB from 4-5PM.

The primary goal of the BEST Center is to foster collaborations between various stakeholders to develop innovative energy efficient and intelligent technologies for buildings, communities, and urban centers. The BEST Center has two university sites, the University of Colorado Boulder (CU) and the City College of New York (CCNY), and University at Albany is a collaborative site, leveraging the diverse academic capabilities of these institutions to benefit our industry partners.

Our IAB members and affiliates represent two utilities, two window manufacturers, one manufacturer of thermal systems and appliances, one electrical systems manufacturer, two building control and distribution systems manufacturers, one municipality, and five engineering consulting companies. In the coming year, we hope to expand the involvement of industry partners to support the building industry's expectations for improved sustainability, resiliency, and intelligence. With our industry partners' support, the BEST Center will continue to be a platform for the building industry to guide universities in educating and training a skilled and diverse workforce to address employment needs for years to come.

We thank all the people who made this event possible, and thanks to all our industry partners, faculty, students, and guests for attending!

Best,
Moncef Krarti, BEST Center Executive Director
Nicholas Clements, BEST Center Manager
Ahmed Mohamed, BEST CCNY Site Director
John Zhai, BEST CU Boulder Site Director
Jorge Gonzalez-Cruz, BEST UAlbany Collaborator Site Director

BEST Center Industry Advisory Board Members and Affiliates

Full Members

Associate Members

Affiliates

Meeting Information

Registration
All attendees, including faculty, students, IAB members, and guests must register:

- **Registration Link** (Eventbrite)

Location
April 24: Advanced Science Research Center (ASRC) Auditorium, **Google Maps Link**
April 25 (**Faculty and IAB Only**): ASRC 1st Floor Seminar Room
Remote Zoom Link: **https://cuboulder.zoom.us/j/6356894174**

April 24, 2025

CCNY: Advanced Science Research Center Auditorium

Remote: https://cuboulder.zoom.us/j/6356894174

Agenda	
8–9AM ET	**Breakfast and Networking**
9-9:30AM ET	**Welcome and Keynote** Luiz Fernando Huet de Bacellar, Eaton VP of Engineering & Tech. *The Future of DC-Powered Buildings*
9:30AM-12PM ET 9:30-9:45AM ET	**FY25-26 Research Proposal Presentations** BEST25-F03: *BatMan Plan - Battery Management & Planning Platform for Cutting Building Electricity Costs by Peak Shaving of Grid Charges with Central and Distributed Batteries,* **Panos Moutis**, Ioannis Vourkas (CCNY)
9:45-10AM ET	BEST25-F01: *Developing a New Paradigm for Deemed Energy Savings of Secondary Window Solutions,* **John Zhai** (CU), Rob Tenent (NREL)
10-10:15AM ET	BEST25-F02: *Evaluation of Energy Efficiency and Operational Performance of Water Source Heat Pump Networks and their Control Strategies through Digital Twin Integration,* **Gregor Henze**, Jonas Søgaard (CU)
10:15-10:30AM ET	BEST25-F04: *Assessment of the Energy Efficiency of DC-Powered Buildings,* **Nicholas Clements**, Moncef Krarti (CU Boulder), Ahmed Mohammed (CCNY)
10:30-10:45AM ET	BEST25-F05: *Embodied Energy and Embodied Carbon Analysis of Residential & Commercial Building Envelopes,* **Wil V. Srubar III**, Jay Arehart, Jonathan Broyles (CU)
10:45-11AM ET	BEST25-F06: *A Digital Twin for Air Source Heat Pump Systems for Single and Multi-Family and Light Commercial Buildings,* Prathap Ramamurthy (CCNY), **Jorge E. González-Cruz** (University at Albany)
11-11:15AM ET	BEST25-F07: *Development of a Flexible Electrification Retrofit Tool for Existing Buildings,* **Moncef Krarti**, Phani Vadali (CU), James Zarske (Noresco)
11:15-11:30AM ET	BEST25-F08: *Impact on Energy Usage of Retrofitting Water Distribution within Buildings with Pressure Independent Solutions Including Typical Human Behavior,* **Eric Ohene**, Moncef Krarti (CU)
11:30-11:45AM ET	BEST25-F09: *Automated Airborne Pathogen Transmission Risk Detection and Control,* **Nicholas Clements** (CU), Phil Arnold (SafeTraces)
11:45AM-12PM ET	BEST25-F10: *Evaluation of Integrated Water Source Heat Pump with Solar Electric and Thermal Storage Systems,* **Phani Vadali** (CU), Moncef Krarti (CU), Amit Bhardwaj (CU), Ivan Smalyukh (CU), Gregor Henze (CU)

12:00-1:00PM ET	**Lunch**
1:00-2:40PM ET	**FY24-25 Project Presentations**
1:00–1:20PM ET	BEST24-01: *Enhancing Thermal Energy Harvesting and Storage using Monolithic Mesoporous Metamaterials (MMMs) and Phase Change Materials (PCMs)*, **Ivan Smalyukh**, Amit Bhardwaj (CU)
1:20-1:40PM ET	BEST24-02: *Embodied Energy and Embodied Carbon Analysis of Residential & Commercial Building Envelopes*, **Megan Quinn**, Wil V. Srubar III, Matthew A. Jungclaus, Jonathan Broyles (CU)
1:40-2:00PM ET	BEST24-03: *Feasibility Evaluation of Net-Positive Window Systems*, **Eric Ohene**, Moncef Krarti, Michael McGehee (CU)
2:00-2:20PM ET	BEST24-04: *Design & Techno-Economic Assessment Tool for ASHP Systems for Cooling, Heating and Hot Water*, **David Garraway**, Prathap Ramamurthy (CCNY), Jorge Gonzalez-Cruz (U at Albany)
2:20-2:40PM ET	BEST24-05: *Performance Evaluation and Grid Impacts of Intelligent Field Devices and Next-Generation Heat Pumps with an Application to Adaptive Reuse of Commercial Buildings*, **Jonas Søgaard**, Gregor Henze, Alex Pentecost (CU)
2:40-3PM ET	**Closing Remarks and Refreshments**
3-4PM ET	**Lightning Poster Session**
4-5PM ET	**IAB Closed Meeting (IAB Members and Affiliates Only)**, ASRC First-Floor Conference Room
5:30-7PM ET	**Dinner (Faculty, Students, IAB Members and Affiliates Only)**, Fumo Harlem (Google Maps Link), 1600 Amsterdam Ave, New York, NY 10031

Day 1 Faculty Instructions: Please respond to proposal feedback from the IAB by midnight, 4/24/25. Your responses will be reviewed with the board during the proposal discussion on 4/25/2025.

April 25, 2025 (Faculty and IAB only)

CCNY: Advanced Science Research Center 1st Floor Seminar Room
Remote: https://cuboulder.zoom.us/j/6356894174

Agenda	
8–8:30AM ET	**Breakfast**
8:30-10AM ET	**Proposal Review with Faculty**
10AM-11AM ET	**IAB Closed Meeting – Proposal Voting**
11AM-12PM ET	**IAB Leadership Meeting**

Lightning Poster Session Instructions

For IAB members and affiliates, please start at your assigned poster on the table below. Guests can start at a poster of your choosing. Every 10 minutes we will request that everyone rotates to a new poster. ***Please ensure each poster has an audience for each 10-min session!***

Presenter Name (Affiliation)	**Poster Title**	**Starting IAB Member**
David Garraway (CCNY)	Design Tools for Assessing Heat Pump performance in Temperate Climates **(FY24-25 Project)**	Rheem
Megan Quinn (CU Boulder)	Embodied Energy and Embodied Carbon Analysis of Residential & Commercial Building Envelopes **(FY24-25 Project)**	Con Edison
Eric Ohene (CU Boulder)	Feasibility Evaluation of Net-Positive Window Systems **(FY24-25 Project)**	Eaton
Jonas Soegaard (CU Boulder)	Performance Evaluation and Grid Impacts of Intelligent Field Devices and Next-Generation Heat Pumps with an Application to Adaptive Reuse of Commercial Buildings **(FY24-25 Project)**	Belimo
S M Abdur Rob (CCNY)	Optimal Control of Superheat for Air Source Heat Pump Systems in Northeastern U.S Winter Climates	Bes-Tech
Jatin Jain, Tanvir Rahman, Mohamed Ali (CCNY)	Detailed Techno- Economic Performance and Feasibility analysis of Residential Virtual Power Plant	
Mohammed Elsayed (CCNY)	Feasibility of Full Vehicle Electrification and V2G Integration in Dense Urban Regions: The Harlem Case	
David Kirakosian, Khairy Sayed (CCNY)	Load Resonant-Tank High-Frequency Inverter for High-Efficiency Wireless Power Transfer-based E-scooters Chargers	
Kirn Zafar (CCNY)	Revolutionizing Active Distribution Network Control: Complex Network Theory Paradigm	
Abrar Abdelbary (CCNY)	Enhancing Energy Resilience in Vulnerable Urban Communities	
Phani Vadali (CU Boulder)	Development of an Automated Electrification Retrofit Analysis Tool	
Haiying Peng (CU Boulder)	Evaluation of Hygrothermal and Energy Efficiency and Condensation Risk of Secondary Windows	

FY2025-2026 Research Proposal Executive Summaries

BEST25-F01: *Developing a New Paradigm for Deemed Energy Savings of Secondary Window Solutions*

John Zhai (CU), Rob Tenent (NREL)

Windows contribute significantly to energy losses, accounting for up to 25-30% of heating and cooling energy consumption in buildings (Berardi, 2017; Paulos & Berardi, 2020). The Fenestration and Glazing Industry Alliance (FGIA) reported steady growth in residential window replacements (FGIA, 2022). However, replacing existing windows as part of building retrofits presents several challenges, including, but not limited to, high cost, time-consuming installation process, and significant disruption to occupants. While secondary window solutions offer cost-effective ways to improve thermal performance, their adoption remain limited (Smith et al., 2012). A key barrier is the lack of standardized methods and user-friendly tools to quantify their energy savings and peak demand reduction potential.

This project aims to establish a new paradigm for quantifying energy savings from secondary window solutions by integrating laboratory testing, energy modeling, and real-world validation. It will develop a standardized framework for evaluating the energy efficiency benefits of secondary windows, enabling policymakers, utility programs, and building owners to confidently incorporate them into energy efficiency initiatives. The results will help address current knowledge gaps and support the broader market adoption of secondary window technologies. The proposed research tasks include:

(i) Laboratory Testing: Conduct controlled experiments to quantify the improvements in thermal transmittance (U-value), reductions in solar heat gain coefficient (SHGC), and changes in air leakage rates.
(ii) Energy Modeling: Perform a comprehensive series of simulations using tools such as WINDOW, THERM, and EnergyPlus to evaluate the performance of secondary windows across different climates, building types, and window configurations.
(iii) Framework Development and Validation: Develop a standardized framework for evaluating the energy and cost efficiency benefits of secondary window solutions based on the above results and validate it through field measurements.
(iv) User-Friendly Tool Development: Develop a user-friendly calculation tool based on the validated evaluation framework.

This research builds upon previous studies on the energy efficiency of building envelopes and the hygrothermal performance of secondary window solutions. The anticipated outcomes include: (1) **A validated methodology for evaluating the energy savings potential of secondary windows. (2) A calculation tool to assess the energy and cost efficiency performance of secondary windows.**

The impact of this project extends beyond energy efficiency improvements. By demonstrating the contribution of secondary windows to reducing greenhouse gas (GHG) emissions, the findings will support compliance with energy efficiency standards and sustainability goals. The validated framework will also provide a foundation for utility rebate and incentive programs, thereby reducing upfront costs for consumers and accelerating market adoption.
Project success will be measured by three key outcomes: (1) validation of experimental results, (2) deployment of the calculation tool, and (3) achievement of Technology Readiness Level (TRL) 7, indicating a prototype demonstration in an operational environment. This project is expected

to promote broader adoption of secondary window solutions, enhance utility-based incentive programs, and provide quantifiable evidence to support GHG reduction policies.

BEST25-F02: *Evaluation of Energy Efficiency and Operational Performance of Water Source Heat Pump Networks and their Control Strategies through Digital Twin Integration*

Gregor Henze, Jonas Søgaard (CU)

The BEST Center is about bringing together industry stakeholders that are committed to innovate the built environment in terms of sustainability, resilience, and intelligence. Societal drivers for innovation include the housing affordability crisis, the need for adaptive reuse of underutilized commercial real estate and harnessing
the rapidly growing availability of data for enhanced building operations in what could be called the data-energy nexus. Specifically, our IAB members (a) develop novel building systems and equipment, building materials and glazing systems, (b) provide power to an increasingly electrified built environment, (c) design effective solutions for new construction and retrofits that respond to the above societal drivers.

This project provides value to several IAB members by (a) evaluating the performance of novel building systems and equipment, e.g., intelligent field devices, (b) analyzing the impact of design choices and control strategies on electric distribution system operations, (c) enhancing the ability of consulting engineers to evaluate design strategies involving a spectrum of smart and emerging technology options by integrating software industry standards and internationally supported software development efforts. Specifically, this project will create realistic digital twin building models within a high-fidelity building performance simulation framework representing a real-world case study located on 100 Van Ness Boulevard in San Francisco, California, which was converted in 2015. To evaluate the performance benefits of the water loop heat pump system, a counterfactual benchmark system model using four-pipe fan coil units (4P-FCU) with natural gas boiler and cooling tower will be developed.

The digital twin models will eventually be added to a publicly available library of so-called emulators to the Building Optimization Testing (BOPTEST) framework to assess the potential performance benefits of IAB member technology (e.g., intelligent field devices, novel heat pumps with low-GWP refrigerants) when integrated into an existing Modelica- plus-EnergyPlus ("Spawn") modeling environment for an actual adaptive reuse case study in California. Importantly, BOPTEST will be used to assess electric grid impacts of supervisory rule based and advanced control strategies coupled with decentralized control strategies embedded in the smart building systems and components. In summary, this project will develop building models for an actual adaptive reuse project, add support for the integration of IAB member technology into the digital twin building models, and assess a variety of key performance indicators (e.g., emissions and electric grid impacts) for an adaptive reuse case study coupled with advanced building control.

BEST25-F03: *BatMan Plan - Battery Management & Planning Platform for Cutting Building Electricity Costs by Peak Shaving of Grid Charges with Central and Distributed Batteries*

Panos Moutis, Ioannis Vourkas (CCNY)

Most typically, a utility charges its customers, primarily, for their energy use and, additionally, for their peak loads over a billing period. The latter charges are called peak pricing and are significantly high to discourage customers' peak loads, which saves a utility from equipment wear and tear and costly energy purchases in electricity markets. Due to fuel price volatility and ageing grid equipment, peak pricing will become even more costly to customers. We will develop the platform "BatMan Plan" to optimally size and control battery storage systems (BSSs) at individual and building levels for peak pricing savings.

BatMan Plan will be trained from renowed load databases to project peak loads and black-swan events using exclusively sensing on customers' load. The platform will also actuate controllers that serve peak demand through BSS energy that has been timely recharged. Special attention is paid to intricate and ever proliferating types of loads such as electric vehicles, data centers and heating/cooling. Probabilistic control will ensure that BatMan Plan benefits maximally individual customers with behind-the-meter BSSs and optimally buildings with centrally controlled BSSs. The major challenge of this work is the BSS degradation that requires balanced cycling to delay replacement costs while ensuring adequate peak pricing savings; this means we must explore extensive scenarios of load growth and increasing rates of extreme events (fires, floods, snowstorms, blackouts).

BatMan Plan spans several value propositions for several stakeholders who may use the platform as follows:

- Utilities (Xcel & ConEd) can develop or promote BSS subsidies/programs for customers' savings, which will also reduce the utilities' exposure to wholesale electricity prices and the grid wear and tear,
- Controller vendors and OEMs (Eaton, Belimo, PassiveLogic) can program their solutions to control BSS (and by extension demand response) to enable peak pricing savings more effectively based on local load sensing,
- Vendors and OEMs of heating/cooling (Rheem, Western Mechanical Solution) can use platform insights to propose heating/cooling patterns that are not contributing to high costs induced by peak pricing,
- Energy consultancy firms (RMH Group, Mead & Hunt, Group14 and PAE) can propose BSS integration with intricate building load demands (electric vehicle charging, heating/cooling/ventilation, data centers) with novel energy efficiency characteristics and cost savings,
- BSS vendors and OEMs can streamline tailored sales/offers with guaranteed savings,
- Customers can use the platform as a guide to purchasing BSS and controllers for behind-the-meter use.

BEST25-F04: ***Assessment of the Energy Efficiency of DC-Powered Buildings***

Nicholas Clements, Moncef Krarti (CU Boulder), Ahmed Mohammed (CCNY)

The US Department of Energy (DOE) estimates that about 1/3 of a building's total energy load runs on direct current (DC) devices, such as LED lighting, electronics, and variable speed drives. Inefficiencies related to converting from AC to DC to power these devices can result in 10-20% reductions in overall energy efficiency. Currently, renewable energy generation and storage technologies (e.g., PV, electrical vehicle charging/storage, and batteries) must be converted from DC to AC to be connected and integrated with building's electrical distribution systems. While not presently commonly considered or even feasible, fully DC-powered buildings could offer significant energy efficiency benefits over AC, particularly when considering recent advancements in NEC Class 4 fault managed power distribution systems. Fault managed power systems, or Class 4 Power as defined in the 2023 National Electrical Code (NEC), is a promising approach to AC-to-DC building conversion allowing 450 VDC over similar cabling as low voltage power-over-ethernet (PoE). Class 4 circuits are constantly monitored for fault events, reducing the risk of shock or fire while distributing high voltages, and they allow data transmission, enabling building system automation and monitoring. There are currently limited field or lab studies assessing the energy performance and cost of implementation for buildings served by DC distribution systems, and with the advent of fault managed power, a thorough analysis of DC-powered buildings, some of which are served by Class 4 Power for specific building systems, is needed. This project aims to quantify the energy efficiency performance and cost benefits of four DC-powered buildings and either simulate a comparable building operating with AC power (i.e., new build DC powered building) or leverage pre-post AC-to-DC conversion utility data to assess the energy saved by the DC conversion. Through site visits and information provided by building owners and managers, case studies will be developed summarizing the implementation and operational costs, maintenance and management requirements, and energy performance of buildings containing DC-powered building systems. Recommendations for future research and development needs for DC-buildings will be developed based on the results of the case studies.

BEST25-F05: ***Embodied Energy and Embodied Carbon Analysis of Residential & Commercial Building Envelopes***

Wil V. Srubar III, Jay Arehart, Jonathan Broyles (CU)

The objectives of this BEST Center project are (1) to define the first science-based benchmarks for *embodied energy* intensity (EEI) (MJ/m2) (or BTU/ft2) and *embodied carbon* intensity (ECI) (kgCO2/m2) (or kgCO2/ft2) for new commercial building envelopes (*i.e.*, wall assemblies) in the US and (2) to develop and deploy an analytical tool that will give architects, engineers, and manufacturers an ability to quickly quantify the embodied energy and embodied carbon savings (or penalties) of new or alternative commercial building envelopes compared to the established benchmarks.

During academic year 2025-2026, this BEST Center project will focus on embodied energy intensity (EEI) (MJ/m2) and embodied carbon intensity (ECI) (kgCO2/m2) benchmarking of *medium and large commercial office building envelopes (i.e., wall assemblies)*. The project will be divided into five tasks. Task I will define typical commercial building envelopes. Task II will define material use intensities (MUIs) (kg/m2) of those assemblies using the US DOE medium and large commercial office building prototype building models as the starting basis for analysis. Task III and IV will define the EEIs (MJ/m2) and ECIs (kgCO2/m2) of these prototype buildings. Task V will develop an analytical tool to compare the EEI and ECI of new or alternative medium and large office building envelope assemblies compared to the established EEI and ECI benchmarks.

The primary benefits to industry members are two-fold: (1) definition of science-based EEI and ECI benchmarks for medium and large office building envelopes in the US context will enable goal-setting in new building and retrofit projects and (2) a simple analytical tool will enable architects, engineers, and product manufacturers to quantify the potential savings (or penalties) in embodied energy and embodied carbon emissions of new commercial building envelope assemblies compared to the established benchmarks.

BEST25-F06: ***A Digital Twin for Air Source Heat Pump Systems for Single and Multi-Family and Light Commercial Buildings***

Prathap Ramamurthy (CCNY), Jorge E. González-Cruz (University at Albany)

Local and state jurisdictions are aiming to transition to low carbon infrastructure via electrification of key sectors. The building sector in particular accounts for more than two-thirds of greenhouse gas (GHG) emissions in large cities such as New York City. Heat pump systems (HPS) are an excellent growing alternative to this challenge potentially providing most electrified services for cooling, heating and hot water as reflected by the growing sales of units of more than 50% over the past three years, globally and in US. Thus, there are a number of challenges and opportunities in HPS in the markets including: (1) Use of high global warming potential (GWP) refrigerants such as R410A (GWPs >2,000), certain markets are limiting GWP<700, new alternatives are available such as natural refrigerants, that if optimized correctly can achieve this goal, CO_2 (aka R744), is a good example (GWP of 1); (2) Integration with building energy systems such as hot water systems, or building envelopes to optimize load management; and (3) New opportunities for electric grid connectivity for active participation of flexible energy markets such as demand response and/or Time of Use (TOU) rates. Efficient tools to assess on the field operation or during design phases will expand the range of options available to designers and contractors to maximize HPS for retrofit or new facilities benefitting greatly the rapidly growing markets. Digital Twins are promising emerging data-driven tools that can assist in improving both designs and operations.

The main goal of this project is to develop an efficient and usable Digital Twin of Air Source Heat Pump Systems (DT-ASHPS) for the design of new or to improve performance of multi-families and light commercial buildings that supports optimization of system performance and costs when integrated into existing or new building energy systems, including hot water, building envelopes, and grid-connection both thermally and electrically. The Specific objectives are:

1. Develop an energy and economic performance Digital Twin (DT) tool to assimilate actual buildings' architectures and optimize ASHPS operations when integrated into new or existing buildings;
2. Identify control strategies for optimal integration and improved operations of ASHPS and grid connectivity;
3. Validate the DT with actual buildings data on the field and with their energy systems;
4. Demonstrate adaptability, transferability, scalability, environmental and cost-benefits in multiple buildings and system scenarios.

BEST25-F07: ***Development of a Flexible Electrification Retrofit Tool for Existing Buildings***

Moncef Krarti, Phani Vadali (CU), James Zarske (Noresco)

The goal of the project is to develop a flexible analysis tool to recommend retrofit measures to optimally electrify existing buildings. The tool will accommodate various building types and retrofit technologies using an optimization-based analysis approach. The tool will be developed using a tested automated calibration approach for detailed building energy models as data-driven models. The proposed flexible analysis tool can be primarily used to electrify both residential and commercial buildings. However, the tool can be applied to perform any retrofit assessment using level 1, 2, or 3 energy audit protocols. Specifically, the tool will be able to (i) investigate various electrification retrofit options for existing buildings and compare their cost benefits including their implementation costs as well as energy, cost, and environmental benefits; (ii) estimate performance metrics such as energy savings, thermal comfort levels, as well as cost benefits of various heat pump options including air source and ground source heat pumps; and (iii) assess different electrification options retrofits combining both building envelopes HVAC systems such as the impacts of retrofit windows on the capacity of the required heat pumps to electrify buildings. The developed electrification retrofit analysis tool will be applied to at least four case studies to assess its performance and refine its capabilities. Moreover, the tool will be developed to be flexible and adapted to the industry needs including utilities, equipment manufacturers, and service providers.

BEST25-F08: ***Impact on Energy Usage of Retrofitting Water Distribution within Buildings with Pressure Independent Solutions Including Typical Human Behavior***

Eric Ohene, Moncef Krarti(CU)

Water distribution systems within buildings are a major yet often overlooked contributor to energy consumption, accounting for up to 15% of total building energy use in the U.S. Most of this energy consumption is attributed to heating and pumping water. While pressure management strategies have been applied at urban and municipal levels, there remains a significant gap in research and practice around building-level interventions, especially those that integrate both technological upgrades and occupant behavior. This study proposes a comprehensive framework for retrofitting water distribution systems using pressure-independent solutions such as Pressure Independent Control Valves (PICVs), Dynamic Pressure-Regulating Valves (DPRVs), and smart, IoT-integrated pressure zones. These technologies improve hydraulic stability, reduce energy waste, and maintain consistent flow and temperature. However, limited research exists on their long-term effectiveness, especially across different climates, building types, and user behaviors. This proposed project will use a mixed-methods approach involving energy audits, user experience surveys, and parametric and optimization analyses to evaluate performance of residential and commercial building water distribution systems retrofitted with pressure-independent technologies. A custom simulation environment will also be developed to test retrofit configurations and behavior-based scenarios, optimizing energy efficiency and user comfort. By bridging engineering and human factors, this research offers a replicable, data-driven pathway for improving the efficiency of building water distribution systems. The anticipated outcomes include measurable reductions in energy consumption, improved water conservation rates, insights into user engagement strategies to optimize water use, and cost benefits of the retrofit options. The findings will inform retrofit strategies, guide policy and investment, and support the broader adoption of sustainable water-energy systems to contribute meaningfully to the goals of energy efficiency in the built environment.

BEST25-F09: ***Automated Airborne Pathogen Transmission Risk Detection and Control***

Nicholas Clements (CU), John Zhai (CU), Phil Arnold (SafeTraces)

The indoor transmission of airborne pathogens, such as COVID-19 and influenza, significantly impacts global health and wellbeing. Strategies exist, such as ASHRAE Standard 241, to mitigate the risk of airborne pathogen transmission through increased ventilation and air cleaning, though the impact of such approaches on energy consumption is not yet understood. This proposal aims to develop and validate an automated strategy for reducing airborne pathogen transmission risk using a network of sensors and real-time ventilation control and evaluate the energy consumption of this approach compared to alternative strategies. First, a novel apparatus will be built to accurately measure the particle size distribution of respiratory emissions (i.e., talking, coughing) from human participants using a vertically oriented duct, overcoming issues in prior studies that used horizontal ducts prone to underestimation of large particles due to gravitational settling. Measured particle size distributions will be incorporated into an existing tracer-scaled risk model, which incorporates measurements of synthetic DNA-based aerosol tracers that simulate the emission and transport of respiratory aerosols in an indoor space. The updated tracer-scaled risk model will then be implemented in a real-time simulation environment and used to predict transmission risk in a chamber testing setting based on number of occupants, ventilation rates, and detection of emission events. Sensors for measuring occupancy (e.g., people counter, CO_2 monitor) and speaking/coughing events (e.g., microphone using AI-based audio signal processing) incorporated into the building automation system will allow real-time risk estimation using this model, and chamber HVAC systems will be programmed to respond in real-time to reduce the risk of disease transmission by meeting the equivalent clean airflow (ECA) rates prescribed in ASHRAE 241 Infection Risk Management Mode (IRMM). The performance of this automated system in reducing risk and energy consumption by the HVAC system will be compared to the case of normal ventilation (i.e., ASHRAE 62.1) and constant IRMM ventilation rates. The proposed approach uses easy to implement measurements, some of which may already be present in existing building systems, and may be widely adoptable to reduce the impact of seasonal infections and future pandemics.

BEST25-F10: ***Evaluation of Integrated Water Source Heat Pump with Solar Electric and Thermal Storage Systems***

Phani Vidali (CU), Moncef Krarti (CU), Amir Bhardwaj (CU), Ivan Smalyukh (CU), Gregor Henze (CU)

The primary objective of the current project is to explore the energy and cost benefits of integrating thermal energy storage systems with water source heat pumps and solar electric-thermal collectors to serve heating, cooling, and hot water demands of electrified residential buildings. The project is based on a combined design and control optimization to maximize the energy performance of incorporating water source heat pumps with thermal storage tanks, phase change materials, and solar PV thermal collectors. The integrated water source heat pump solar storage system is proposed to have 4 tanks, a hot water tank, chilled water tank, domestic hot water tank and a buffer hot water tank that are connected to a water source heat pump and served by a PV thermal collector, and a battery. A comprehensive evaluation of the energy performance and the cost benefit for the integrated heat pump storage system compared to the conventional air source heat pump will be carried out when deployed for residential buildings across US climates for a wide range of utility rate structures. The analysis will be conducted using a simulation environment to model all the system components using a validated RC network model for building energy analysis. Using a combined optimization approach, design specifications and control settings for the integrated heat pump storage system will be determined for various US climates. Different objective functions for the optimization analysis will be considered including minimization of operational cost, peak demand, and carbon emissions while maintaining acceptable levels of indoor thermal comfort and delivering the required domestic hot water needs. An alternative to solar hot water collector using energy shifting panels to collect and storage solar thermal energy. These innovative panels consisting of transparent thermal insulation materials integrated with phase change materials can be placed on roofs or walls of new or existing buildings. An experimental analysis indicates that these energy shifting panels can store heat for up to 15 hours thereby providing an effective approach to allow using solar energy from the daytime to the nighttime to meet the heating requirements for both indoor spaces and domestic hot water. The project will also develop the specifications for an optimized prototype for the integrated water source heat pump thermal storage system. This prototype can be constructed and tested under controlled laboratory conditions as part of a future project. The primary outcomes of the proposed project include a fully integrated simulation and optimization environment to evaluate different configurations for integrated heat pump storage system, a synthesis on the cost benefits of the integrated system when deployed for different US climates and pricing structures, and a prototype for the system suitable for future testing-based evaluation.

FY2024-2025 Research Project Executive Summaries

BEST24-01: *Enhancing Thermal Energy Harvesting and Storage using Monolithic Mesoporous Metamaterials (MMMs) and Phase Change Materials (PCMs)*

Ivan Smalyukh (CU Boulder)

Renewable energy sources offer promise, but their full potential is hindered by the lack of scalable, affordable, and sustainable energy storage systems. In the United States, buildings are major consumers of electricity, accounting for a staggering 74% of usage. This highlights the crucial role of energy storage within the building sector. While electrochemical batteries have seen advancements in storing electrical energy, concerns about their cost and materials question their suitability for buildings. As an alternative, thermal energy storage (TES) stands out for its affordability, durability, and ability to improve heating and cooling functions. Given that heating and cooling needs constitute over half of a building's energy demand, implementing on-site TES offers a sustainable and scalable complement to electrochemical storage, reducing reliance on traditional power grids and advancing energy independence and sustainability goals. Solar heat can be easily harnessed during the daytime but is often needed during the night time. To achieve this, we combine transparent thermally insulating materials and phase change materials (PCMs) to allow for harnessing the solar heat energy when available and releasing when needed. PCMs, particularly in latent heat thermal storage systems, have gained attention for their ability to store passive solar and other heat gains within a specific temperature range. This results in decreased energy consumption, enhanced thermal comfort through the mitigation of temperature fluctuations, and reduced peak loads. Aerogels present further potential with their high optical transparency and exceptional insulation properties, facilitating heat retention within thermal energy storage systems. Despite challenges such as high costs and fragility, recent breakthroughs in our research group have addressed these issues by developing economically viable monolithic mesoporous metamaterials (MMMs) with exceptionally high insulation values (high R-value/inch), excellent transparency, and durability. These advancements position MMMs as optimal solutions for achieving enhanced thermal energy storage efficiency. This project is focused on maximizing solar energy utilization through MMMs, coupled with PCM to efficiently store thermal energy. The transparency of MMMs enables the absorption of solar radiation by PCM, creating a greenhouse effect, while their insulation properties minimize heat loss, elevating thermal storage efficiency to unprecedented levels. The system allows for efficient collection and storage of thermal energy during the day, which can be used at later times for various applications.

BEST24-02: ***Embodied Energy and Embodied Carbon Analysis of Residential & Commercial Building Envelopes***

Wil Srubar (CU Boulder)

The objectives of this project are (1) to define the first science-based benchmarks for *embodied energy* intensity (EEI) (MJ/m^2 or BTU/ft^2) and *embodied carbon* intensity (ECI) ($kgCO_2/m^2$ or $kgCO_2/ft^2$) for new residential and commercial building envelopes (*i.e.*, wall assemblies) in the US and (2) to develop and deploy an analytical tool that will give architects, engineers, and manufacturers an ability to quickly quantify the embodied energy and embodied carbon savings (or penalties) of new or alternative residential and commercial building envelopes compared to the established benchmarks.

This project will focus on embodied energy intensity (EEI) (MJ/m^2) and embodied carbon intensity (ECI, $kgCO_2/m^2$) benchmarking of *single-family residential building envelopes (i.e., wall assemblies)*. The project will be divided into five tasks. Task I will define typical single-family residential building envelopes. Task II will define material use intensities (MUIs, kg/m^2) of those assemblies using the US DOE single-family residential building prototype building model as the basis for analysis. Task III and IV will define the EEIs (MJ/m^2) and ECIs ($kgCO_2/m^2$) of typical single-family residential building envelopes, respectively. Task V will develop an analytical tool to compare the EEI and ECI of new or alternative single-family residential building envelope assemblies compared to the established EEI and ECI benchmarks.

The primary benefits to industry members are two-fold: (1) definition of science-based EEI and ECI benchmarks for single-family residential building envelopes in the US context will enable goal-setting in new building and retrofit projects and (2) a simple analytical tool will enable architects, engineers, and product manufacturers to quantify the potential savings (or penalties) in embodied energy and embodied carbon emissions of new residential and commercial building envelope assemblies compared to the established benchmarks.

BEST24-03: *Feasibility Evaluation of Net-Positive Window Systems*

Moncef Krarti, Michael McGehee (CU Boulder)

Windows remain the building envelope elements with the weakest thermal performance with limited guidelines for manufacturers and building professionals on the best specifications suitable for a wide range of building types and climates. This project addresses this gap to provide clear recommendations and optical design specifications for both static and dynamic windows to achieve net zero energy performance for office buildings located in representative US climates. Specifically, the project will calculate the energy loss or gain based on U-values and solar heat gain coefficients for windows with many different combinations of insulating strategies (double pane, triple pane, vacuum insulating glass and aerogel) and dynamic tinting strategies (electrochromic, thermochromic, reversible metal electrodeposition.) It will show which windows could be net energy positive and enable the calculation of payback times, which will assist window companies, investors, and architects in deciding which window designs to prioritize. Based on the conducted sensitivity analyses, the project will attempt to provide general guidelines to select thermal/optical properties as well as control strategies and any additional integrated systems required for net positive energy windows when deployed in US office buildings.

BEST24-04: ***Design & Techno-Economic Assessment Tool for ASHP Systems for Cooling, Heating and Hot Water***

Prathap Ramamurthy (CCNY), Jorge Gonzalez-Cruz (U at Albany)

This project aims to begin the novel discovery process for building retrofitting strategies by leveraging the latest advancements in artificial intelligence (AI), machine learning (ML), coupled with EnergyPlus™ and the National Renewable Energy Laboratory's (NREL) REopt tool. With a focused goal of enhancing energy efficiency, ensuring economic viability, and promoting environmental sustainability, this project represents a significant step towards optimizing energy systems across various building types, including commercial, residential, and municipal structures.

At the core of this project is a commitment to achieving a path to substantial energy performance improvements. Forecasting a 30-40% increase in energy efficiency and a 20-30% reduction in peak energy demand, the project's targeted outcomes are ambitious but attainable. These efficiency gains and demand savings are underpinned by a sophisticated methodology that integrates predictive modeling with multi-objective optimization (MOO) techniques. The MOO framework, enriched by AI and ML algorithms, facilitates the identification of optimal retrofitting strategies that balance energy savings with economic and environmental considerations.

Central to the project's methodology is the use of the NREL REopt tool, a techno-economic decision support model that enables the comprehensive analysis of energy systems. REopt's capabilities are extended through the application of AI/ML algorithms, ensuring high-precision predictive modeling of retrofit measures. This integration allows for the evaluation of various energy conservation measures (ECMs) and the determination of their economic and environmental impacts. Through this approach, the project aims to deliver optimized retrofitting plans that demonstrate significant improvements in energy efficiency, carbon emissions reduction, and cost-effectiveness.

BEST24-05: ***Performance Evaluation and Grid Impacts of Intelligent Field Devices and Next-Generation Heat Pumps with an Application to Adaptive Reuse of Commercial Buildings***

Gregor Henze (CU Boulder)

The BEST Center is fundamentally about bringing together industry stakeholders that are committed to innovate the built environment in terms of sustainability, resilience, and intelligence. Some of the societal drivers for innovation include the housing affordability crisis, the need for adaptive reuse of underutilized commercial real estate, and harnessing the rapidly growing availability of data for enhanced building operations in what could be called the data-energy nexus.

Our IAB members (a) develop novel building systems and equipment, building materials and glazing systems, (b) provide power to an increasingly electrified built environment, (c) design effective solutions for new construction and retrofits that respond to the above societal drivers.

This project aspires to provide value for each of these three groups of IAB members by (a) evaluating the performance of novel building systems and equipment, e.g., intelligent field devices, (b) analyzing the impact of design choices and control strategies on electric distribution system operations, and (c) enhancing the ability of consulting engineers to evaluate design strategies involving a spectrum of smart and emerging technology options. Rather than creating yet another software tool, this work will integrate software industry standards and internationally supported software development efforts.