The Building Energy Smart Technologies (BEST) Center

An Industry-University Cooperative Research Center

Built Environment	
Scale	**Attributes**
Buildings	Energy Efficiency & Sustainability
Communities	Intelligence & Controllability
	Resiliency & Reliability
Urban Centers	Affordability & Cost-Effectiveness
	Comfortable & Healthy Environments
	Occupant Productivity

Demand Side: Building Envelope · Lighting Systems · Equipment & Appliances · HVAC Systems

Management: Distribution Systems · Control Systems

Supply Side: Renewable Power Generation · On-Site Energy Storage · Utilities, Grids, & Microgrids

https://best-iucrc.org/

University of Colorado Boulder

NSF

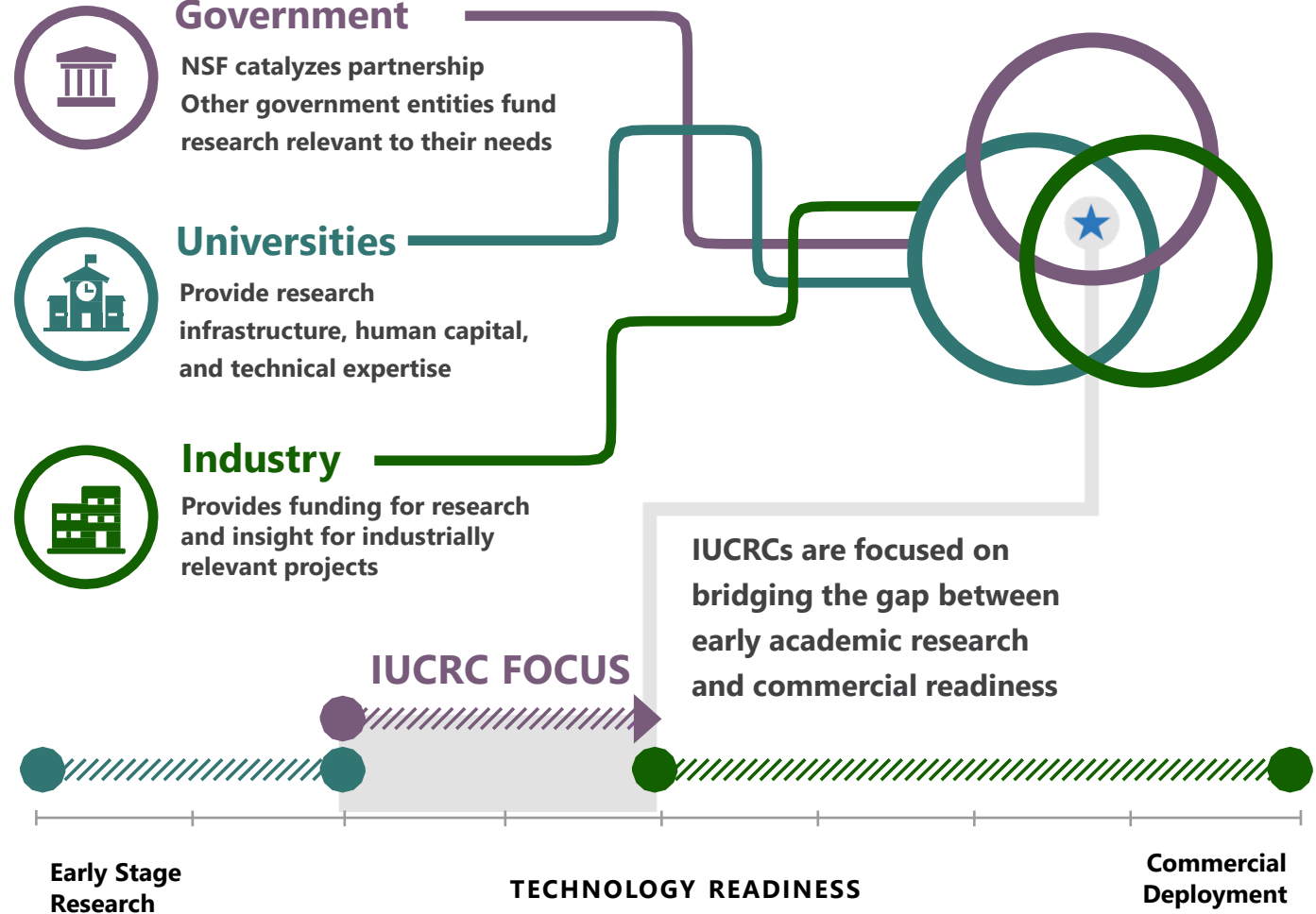The City College of New York

The BEST Center is operated using the NSF model for Industry-University Cooperative Research Centers (IUCRCs):

Long-term partnerships are developed among industry, universities, and government agencies

Funds are provided by NSF to cover the operation and management costs

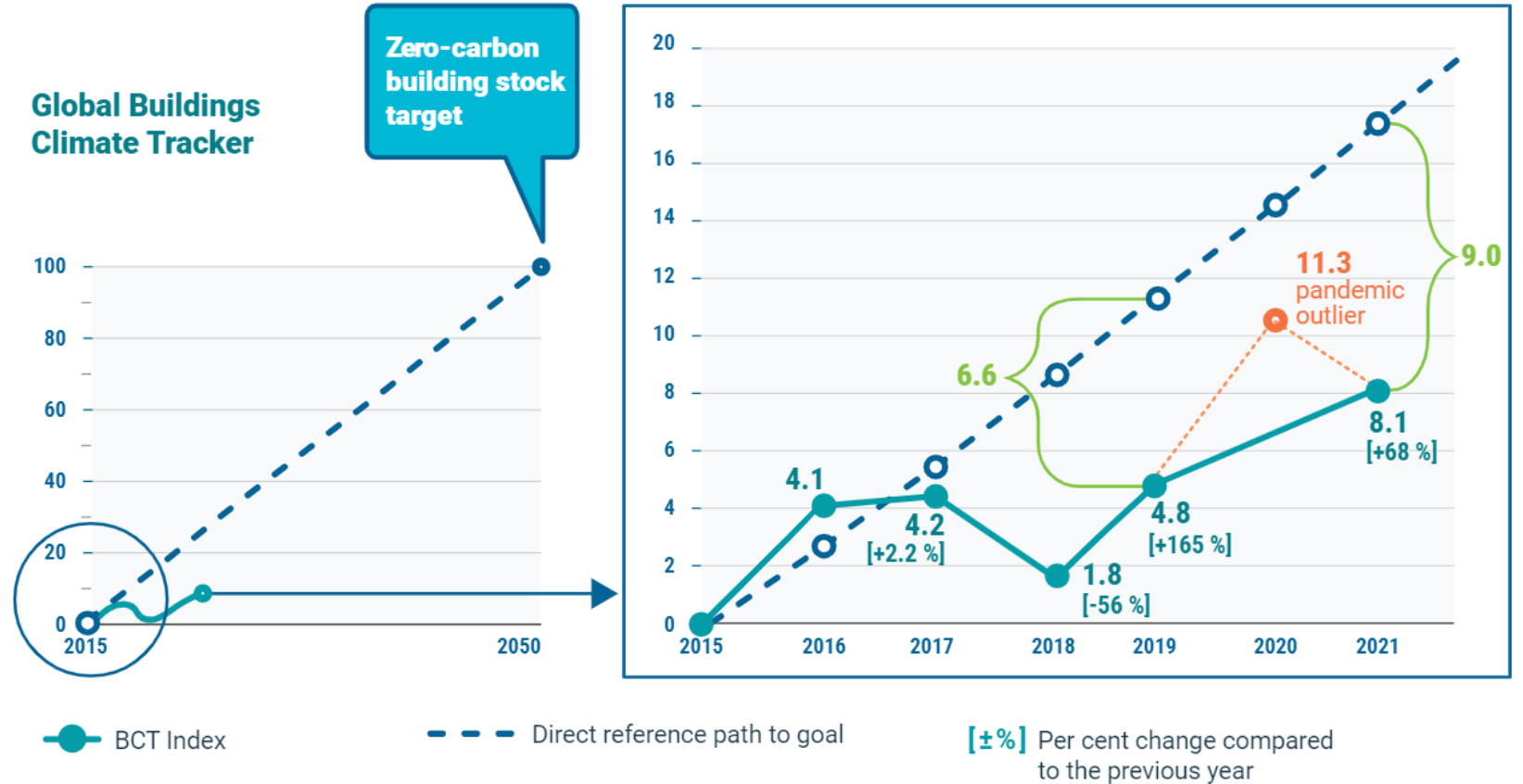**Industry advisory board (IAB) member fees fund research, education, and training activities**

Government
NSF catalyzes partnership
Other government entities fund research relevant to their needs

Universities
Provide research infrastructure, human capital, and technical expertise

Industry
Provides funding for research and insight for industrially relevant projects

IUCRCs are focused on bridging the gap between early academic research and commercial readiness

IUCRC FOCUS

Early Stage Research

TECHNOLOGY READINESS
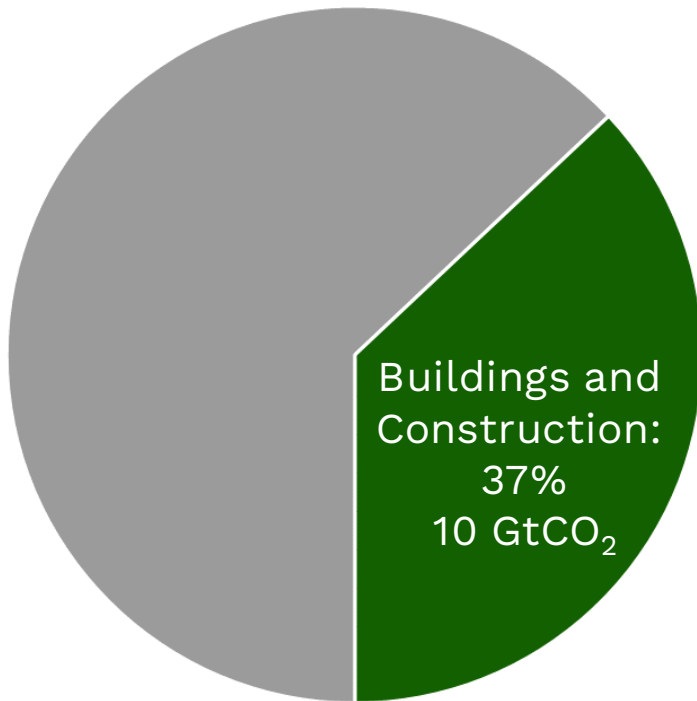
Commercial Deployment

https://iucrc.nsf.gov/

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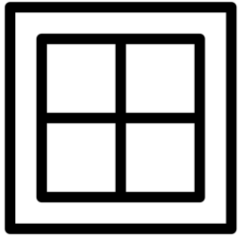# Decarbonizing Buildings and Cities is Critical...

...but we're falling behind reaching zero-carbon building stock by 2050 and CO_2 emissions from the building sector continue increasing

2021 Global CO_2 Emissions

Buildings and Construction: 37% 10 $GtCO_2$

Global Buildings Climate Tracker

Zero-carbon building stock target

11.3 pandemic outlier

9.0

6.6

4.1

4.2 [+2.2 %]

1.8 [-56 %]

4.8 [+165 %]

8.1 [+68 %]

BCT Index — Direct reference path to goal

[±%] Per cent change compared to the previous year

<u>2022 UN Global Status Report for Buildings and Construction</u>

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BEST Center Research Themes

Innovative Building Materials
Dynamically adaptive building shells and envelope systems adjust to changes in indoor and outdoor environments and effectively meet structural & efficiency requirements.
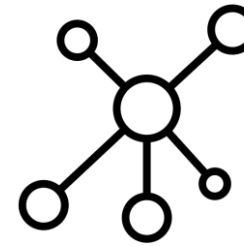
Smart Buildings & Cities
Integrate energy efficiency technologies, advanced controls, and renewable energy resources to improve building and city design and operation.
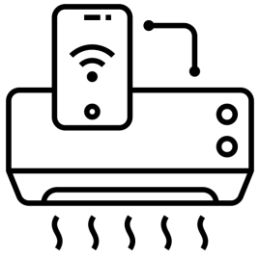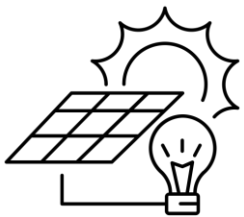
Advanced Energy Systems
Enhance the energy efficiency of various building systems and equipment to meet occupants' comfort and health needs and increase their productivity.

Intelligent Grid Systems
Operate an increasing number of distributed energy resources to exchange optimally and efficiently energy between the electric grid and buildings.

## Integrated Energy Generation & Storage Systems
Such systems include solar power integrated into building envelopes, combined heat and power systems, and thermo-electric generators.
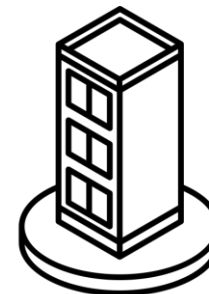
Building Retrofit Applications
Improve energy efficiency and operation of existing buildings, including upgrades of the electrical, lighting, envelop, thermal systems, and controls in an existing buildings.

BEST Center Site Expertise
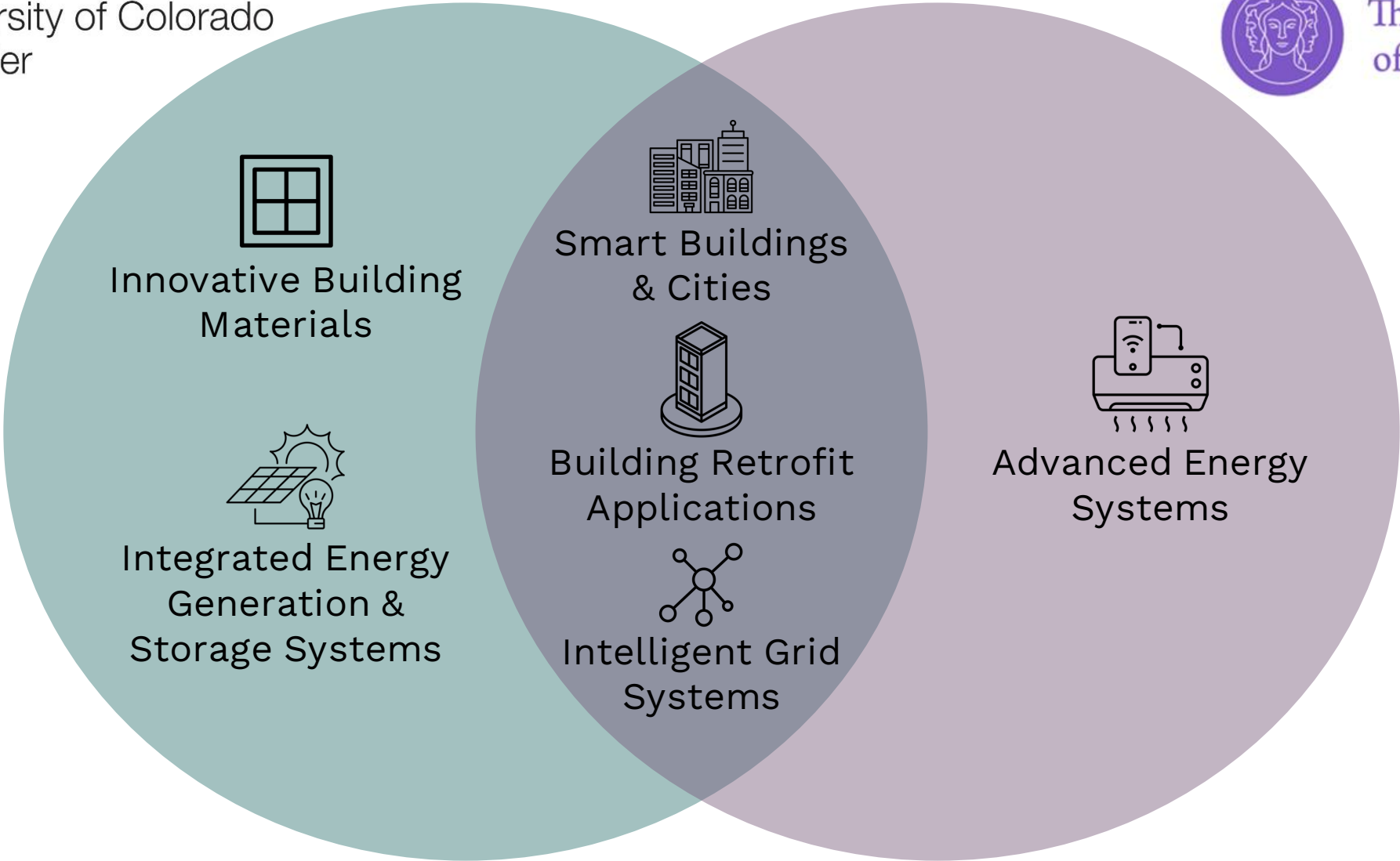
Status of the BEST Center

- NSF IUCRC Phase I Period: 8/1/2021-7/31/2026
- University sites: University of Colorado (CU), City College of New York (CCNY)
  - Collaborator site: University at Albany
- Website: https://best-iucrc.org/
- LinkedIn: https://www.linkedin.com/in/best-center/
- Industry Advisory Board (IAB) Membership: 4 Full, 3 Associate, and 6 Affiliates
- Awarded $865,000 in funding through FY24-25 for 17 research projects
- IAB meetings held biannually in the fall and spring, virtual meetings monthly
- IAB members and affiliates mentor students and provide material support

Fall: IAB Meeting
Faculty & IAB establish annual research topics

Winter: Proposal Preparation
Faculty prepare proposals

IAB reviews proposals

Spring: IAB Meeting
Faculty/students present proposals & research results

IAB makes funding recommendations

Summer: Research Funding Awarded
Funding is awarded to funded project PIs & research projects start

# BEST Center Funded Research 2024-2025

Enhancing Thermal Energy Harvesting and Storage using Monolithic Mesoporous Metamaterials (MMMs) and Phase Change Materials (PCMs)
Smalyukh (CU)
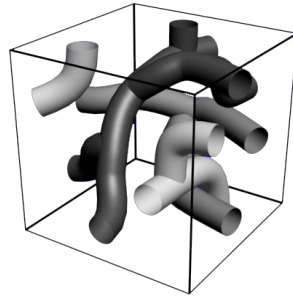
Design & Techno-Economic Assessment Tool for ASHP Systems for Cooling, Heating and Hot Water
Ramamurthy (CCNY), Gonzalez-Cruz (UAlbany)

Embodied Energy and Embodied Carbon Analysis of Residential & Commercial Building Envelopes
Srubar (CU)
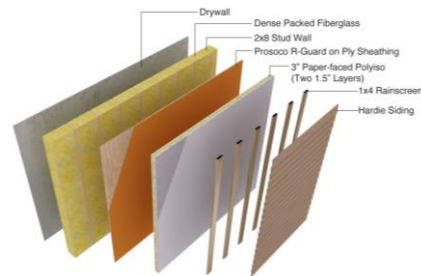
Performance Evaluation and Grid Impacts of Intelligent Field Devices and Next-Generation Heat Pumps with an Application to Adaptive Reuse of Commercial Buildings
Henze (CU)
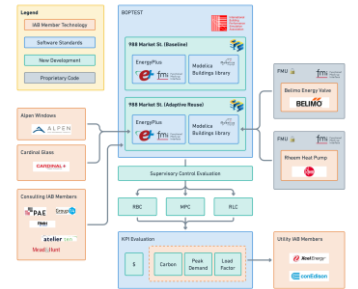
Feasibility Evaluation of Net-Positive Window Systems
Krarti (CU), McGehee (CU)

Executive summaries available at:

https://best-iucrc.org/research-projects/

Industry Advisory Board (IAB)

- Assist with strategic planning
- Vote on proposals to receive funding during spring IAB meetings and research topics for the annual request for proposals (RFP) during fall IAB meetings
- Monitor progress and execution of funded projects
- Mentor student researchers and provide material support
- Identify industrial internship and employment opportunities for students
- Attend biannual IAB meetings to provide feedback on projects and proposals
- Support recruiting new IAB members

IAB Chair, 2023-2024
Sachin Nehete
Rheem

IAB Vice Chair, 2023-2024
Silvia Khurrum
Con Edison

Industry Advisory Board Members

Full Members (4 votes, 1 vote/member)

Associate Members
(1.5 votes, 0.5 vote/member)

Affiliates

Industry Advisory Board Verticals

Utilities
Xcel (Full)
ConEdison (Full)

HVAC & Thermal Systems
Rheem (Full)

Windows
Cardinal (Full)
Alpen (Associate)

Municipalities
City of Boulder (Affiliate)

Consulting
RMH Group (Associate)
Group14 (Affiliate)
Atelier Ten (Affiliate)
Mead & Hunt (Affiliate)
PAE Engineers (Affiliate)

Controls & Sensors
Belimo (Associate)

Industry Partner Benefits

Recruiting

Streamline access to students trained in industry verticals

Contribute to BEST center research and education programs as mentors and thesis committee members

Host undergraduate and graduate students as interns and access NSF INTERN funding

Research & Development

Leverage NSF funds to conduct high risk projects

Access state-of-the-art facilities and research capabilities to develop products and conduct independent testing

Have non-exclusive rights to the entire BEST center shared research portfolio

Networking & Training

Stay informed about the state-of-art in smart and efficient building technologies

Collaborate and interact with industry partners, faculty, and students

Develop custom-made training sessions for employees and provide training to faculty and students

Industry Advisory Board
Membership Levels and Benefits

	Full Membership	Associate Membership	Affiliation
Annual Dues	$50,000	$25,000	<$25,000
Vote #	1	0.5	0
Royalty-Free IP Licensing	✓	✓	✗
Access to Shared Research Products	✓	✓	✓
Project Mentoring	✓	✓	✓
Provide Feedback on Center Strategy	✓	✓	✓

Fall 2024 IAB Meeting

- Locations: Boulder, CO, New York, NY, and Zoom

- Date: October 28, 2024

- Time: 8-3 MT (10-5 ET)

- Presentations: FY24-25 project scopes and planning

- Networking: Whiteboard session to discuss research needs to develop research topics for the FY25-26 RFP

- Registration: Link

- Website: Link

https://best-iucrc.org/

BEST Center Funded Research 2023-2024

Sustainable Air Source Heat Pump Systems for Electrified Transition Markets in the Multi-Family Buildings Sector
PIs: Gonzalez-Cruz (UA), Ramamurthy (CCNY)

- Aims to prototype, test, design, and further develop electrical air-source heat pumps (ASHP) for hot water, space heating & cooling (Tri-Service) for multi-family buildings.
- Systems will specifically focus on the use of R410 as transitional & transcritical carbon dioxide (TR-CO2) systems as developmental.

Development of an Automated Electrification Retrofit Analysis Tool
PIs: Krarti, Zarske (CU), Prahl (CCNY)

- Aims to integrate an existing energy audit tool with optimization framework to select best possible combination of energy conservation measures for an auto-calibrated building energy model.
- Demonstrate the effectiveness of the tool for existing housing units in Boulder, CO and New York City.
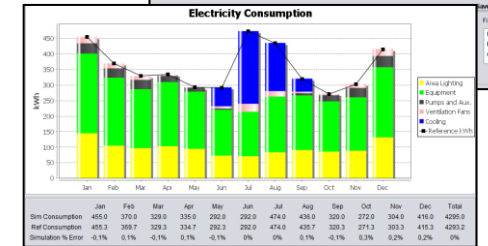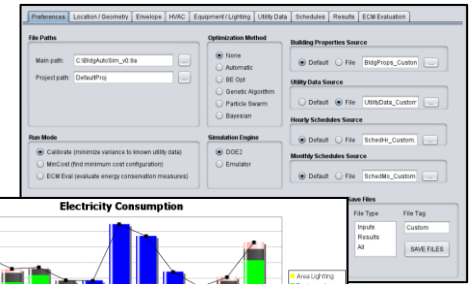
Evaluation of Field Methods for Assessment of Architectural Window Degradation
PIs: Zhai (CU), Tenent (NREL)

- Determine effectiveness of different window thermal field measurement techniques (U-factor, VLT, SHGC, low-e performance, etc.)
- Understand window deterioration mechanisms through theoretical analysis and perform wide-scale field tests
- Relate window durability and thermal performance
- Integrate relationship into energy modeling software
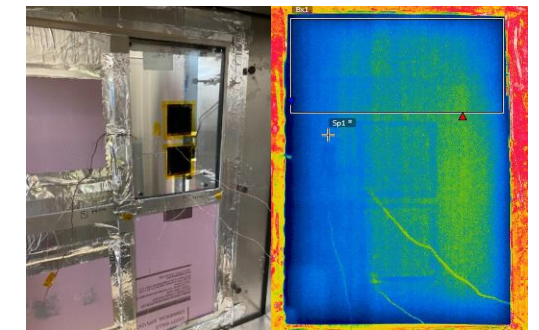
# BEST Center Funded Research 2023-2024

Testing and Evaluation of Thermal Energy Storage Panels Integrated with Heat Pumps
PI: Krarti (CU), Kishore (NREL)

- Develop designs of integrated plug-in TES panels suitable for deployment in building envelope of existing buildings equipped with heat pumps.
- Evaluate the energy and cost performance of the integrated TES systems when deployed for US residential buildings in various US climates
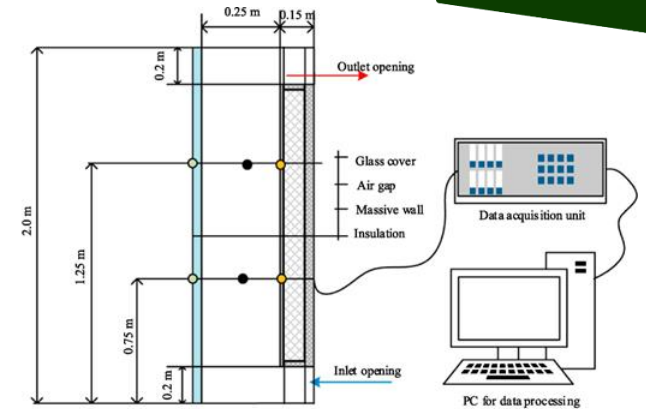
Evaluation of Hygrothermal and Energy Efficiency and Condensation Risk of Secondary Windows
PIs: Zhai (CU), Tenent, Kiatreungwattana (NREL)

- Aims to perform a systematic laboratory testing coupled with a detailed simulation analysis to evaluate the energy efficiency and condensation risks for secondary windows as well as establish a clear set of recommendations for their suitability and cost benefits for various building types and climate zones.
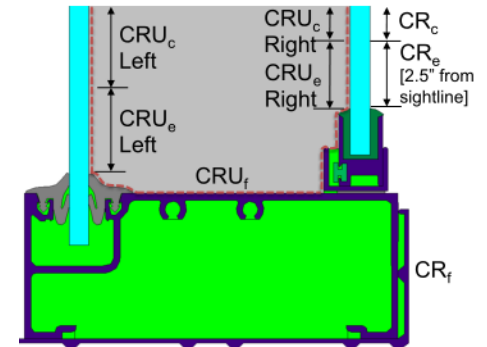
6. Making Reinforcement Learning Practical for Building Control through Human Feedback
PI: Gregor Henze (CU)

- Aims to investigate the benefits of utilizing Human-In-the-Loop (HIL) reinforcement learning as a solution to optimally balance the multiple operational objectives in the management of commercial buildings, addressing real-world challenges and opportunities related to renewable energy sources, harnessing buildings as flexible grid system participants and electric vehicles (EVs) as energy storage devices.
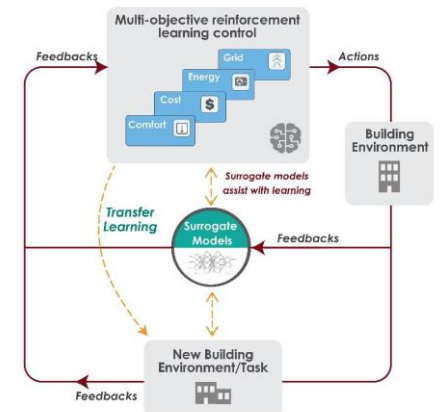
BEST Center Funded Research 2022-2023

## Evaluation of Field Methods for Assessment of Architectural Window Degradation
PIs: Zhai (CU), Tenent (NREL)

- Assess effectiveness of window thermal measurement techniques and theoretical window deterioration mechanisms
- Relate window durability and thermal performance
- Analyze whole building annual energy implication of window deterioration

Integrated and Smart Controls for Combined Heat Pump and Domestic Water Heater for Residential Buildings
PIs: Krarti, Baker (CU), Jin (NREL)

- Develop a platform for simultaneously designing and controlling heat pumps and water heaters with and without rooftop photovoltaic systems and batteries to enhance energy efficiency and demand response capabilities of electrified residential buildings
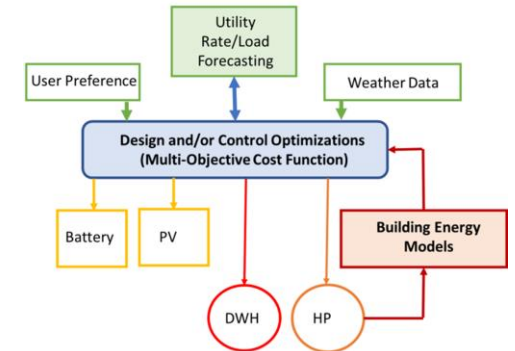
Energy-Reduction M&V using Calibrated Simulation (IPMVP Option D)
PIs: Berk, Prahl (CCNY)

- Generate and calibrate BEMs in automated/semi-automated fashion using building data collected for energy audits or other purposes (e.g., geometry, system info, operation schedules, property attributes)
- Produce and evaluate a prototype BEM workflow for a large portfolio of municipal buildings
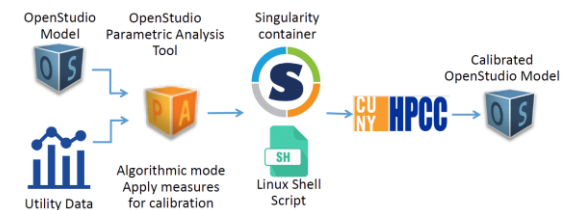
BEST Center Funded Research 2022-2023

Cost-Effective Way to Forecast Energy use at Building to City Scale using Real-Time Satellite Data
PI: Ramamurthy (CCNY)

- Predict/forecast energy use at multiple scales by exploiting the relationship between urban landcover/land use, urban heat island effect, and building energy consumption
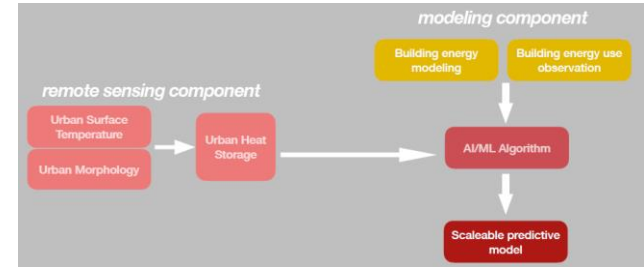- Couple satellite-derived storage heat flux data to past climate runs to develop an AI/ML based model to predict urban energy consumption

Flexible Insulated Panels for Retrofitting Existing Building Envelopes
PIs: Krarti, Roudbari (CU)

- Review literature to understand US market for prefabricated panelized systems for residential deep energy retrofits
- Perform energy modeling to determine optimal design for exterior insulated retrofit wall panels
- Develop a design suitable for retrofit applications
- Construct and test a prototype for an insulated panel

Making Reinforcement Learning Practical for Building Control using Surrogate Models
PI: Gregor Henze (CU)

- Use recently completed Advanced Control Test Bed (ACTB) with high fidelity building models that simulate physics and dynamics necessary for controls design and assessment at both supervisory and local loop levels
- Explore techniques that make RL practical and scalable to realistic building scenarios and use of surrogate models and develop recommendations
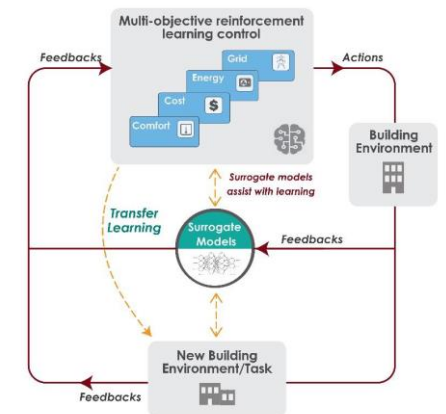
CU Boulder Research Capabilities

Larson Lab
(Clements, Zhai, Krarti)

- HVAC system optimization
- Healthcare ventilation design
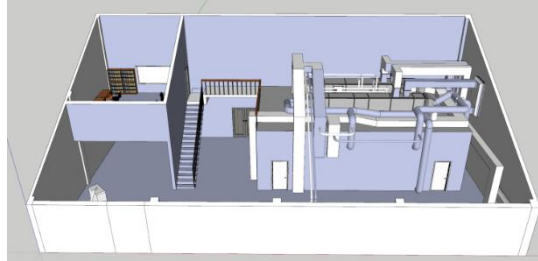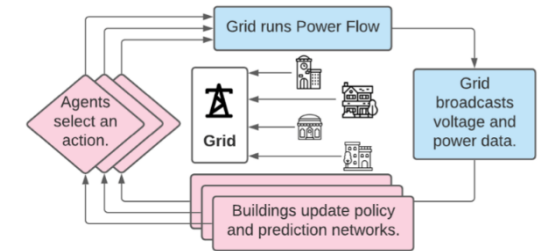- Novel building design and envelope benchtop testing
- Air quality control testing
- Larson Lab Website

Building & Electrical Systems Modeling
(Henze, Baker, Zhai, Krarti)

- Machine learning (ML) for energy systems and renewables
- ML-based predictive control and building energy optimization
- Computational fluid dynamics
- Baker Lab Website

Lighting Lab
(Vasconez, Scheib)

- Dynamic ceiling
- Goniophotometer
- Illumination measurement equipment
- Lighting Lab Website

Solar Cells & Dynamic Windows Lab
(McGehee)

- Perovskite solar cell material properties and efficiency measurements
- Dynamic window tint material properties and design
- McGehee Lab Website

Living Materials Lab
(Srubar)

- Integrates biology with cement chemistry to create sustainable, biomimetic, and living materials
- Structural measurements in lab
- Embodied carbon modeling
- LML Lab Website

Renewable & Sustainable Energy Institute
(RASEI, Baker, Henze, McGehee, Krarti)

- Joint institute between CU and NREL
- Grid innovation research
- Nanoscience for energy capture and conversion
- RASEI Website

CU Boulder Faculty

Prof. Moncef Krarti
- Building energy efficiency technologies
- Optimal design & retrofit of buildings
- HVAC & lighting controls
- Benefit analysis of large-scale energy efficiency programs
- Renewable energy system assessment

Prof. Gregor Henze
- Building-to-grid integration
- Model-based predictive control of building energy systems and thermal mass
- Model-based building performance benchmarking
- Zero energy buildings
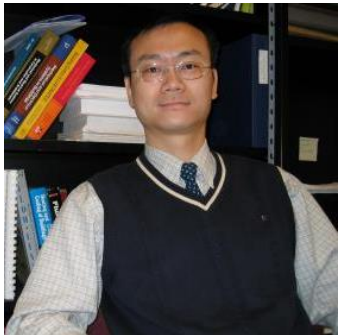
Prof. John Zhai
- Computational fluid dynamics in buildings
- Thermal comfort & indoor air quality
- HVAC systems & heat transfer
- Building vulnerability & safety
- Renewable energy & sustainable building design

Prof. Wil Srubar
- Biomimetic and living materials science & engineering
- Alternative cement & concrete materials
- Embodied carbon of materials & structures

Prof. Kyri Baker
- Power systems
- Smart grids
- Renewable energy
- Building-to-grid optimization
- Energy applications of machine learning

Prof. Michael McGehee
- Perovskite solar cells
- Dynamic windows with adjustable tinting
- Organic LEDs and light extracting LEDs
- Light trapping in solar cells

CCNY Research Capabilities

Building Performance Lab (BPL) (Berk, Prahl, Bobker)

- DCAS Energy Data Lab, collaboration to research NYC energy management
- Validated measurement and verification program for energy efficiency and greenhouse gas reduction activities
- Building optimization support and technical services for quantifying energy savings and producing training materials for NYC personnel
- Application development for energy analytics and diagnostics tools (BEMA, BASAT, VII Calculator, AIRC)
- BPL Website

Coastal Urban Environmental Research Group (Gonzalez-Cruz)

- Observational and modeling research of complex coastal urban areas and their impacts on climate modification
- Integrates the Regional Atmospheric Modeling System (RAMS), Weather Research and Forecasting (WRF) models with building energy models, urban land use data/models, and satellite data
- Social-technical modeling framework for improving resiliency of critical infrastructure for island communities in the event of extreme weather
- CUERG Website

Smart Grid Interdependencies Lab (Mohamed)

- Interdependent critical infrastructure network modeling for grid resilience
- Smart distribution grid integration with regenerative electric rail braking energy
- Microgrid communication-based control scheme modeling
- Food-water-energy nexus data and modeling framework
- SGIL Website

Advanced Science Research Center

- Promotes interdisciplinary research in five disciplines: env. sciences, nanoscience, neuroscience, photonics, and structural biology
- Next Generation Environmental Sensor Lab (NGENS) with reference instruments for atmospheric gases, particulate matter, noise, and thermal imaging
- Design and fabrication of instrumentation and tools
- Community sensor lab
- ASRC Website

CCNY Faculty

Prof. Ahmed Mohamed
- Power and energy systems
- Smart grids
- Critical infrastructure interdependencies
- Microgrids
- Transportation electrification

Prof. Jorge Gonzalez-Cruz
- Urban energy sustainability
- Urban weather and climate
- Urban remote sensing
- Regional climate modeling and analysis

Prof. Prathap Ramamurthy
- Biosphere-atmosphere interactions over complex terrains
- Boundary layer meteorology
- Urbanization, sustainability and climate change

Dr. Mark Arend
- Lidar and atmospheric modeling systems
- Weather forecasts related to energy usage and energy production in urban regions
- WeatherWatt building energy usage modeling

CUNY Building Performance Lab

Honey Berk
- Executive Director, Building Performance Lab

Michael Bobker
- Director, Building Performance Lab

Duncan Prahl
- Senior Applied Research Scientist, Director Technical Services

BEST Center Organizational Structure

Industry Advisory Board (IAB) Members

Executive Director
Prof. Moncef Krarti, CU

CU Site Directors
Prof. Moncef Krarti
Prof. John Zhai

Manager
Dr. Nicholas Clements, CU

CCNY Site Director
Prof. Ahmed Mohamed

CU Research
Community
Faculty and Students

CCNY Research
Community
Faculty and Students

NSF Program Director
Dr. Prakash Balan

NSF Evaluator
Max Green

UA Collaborator Site
Prof. Jorge Gonzalez-Cruz