# The Building Energy Smart Technologies (BEST) Center

## An Industry-University Cooperative Research Center



| Built Environment | | Demand Side | Building Envelope | Lighting Systems | Equipment & Appliances | HVAC Systems |
|---|---|---|---|---|---|---|
| **Scale** | **Attributes** | | | | | |
| Buildings | Energy Efficiency & Sustainability | | | | | |
| | Intelligence & Controllability | Management | Distribution Systems | | Control Systems | |
| Communities | Resiliency & Reliability | | | | | |
| | Affordability & Cost-Effectiveness | | | | | |
| Urban Centers | Comfortable & Healthy Environments | Supply Side | Renewable Power Generation | On-Site Energy Storage | Utilities, Grids, & Microgrids | |
| | Occupant Productivity | | | | | |

https://best-iucrc.org/

University of Colorado Boulder
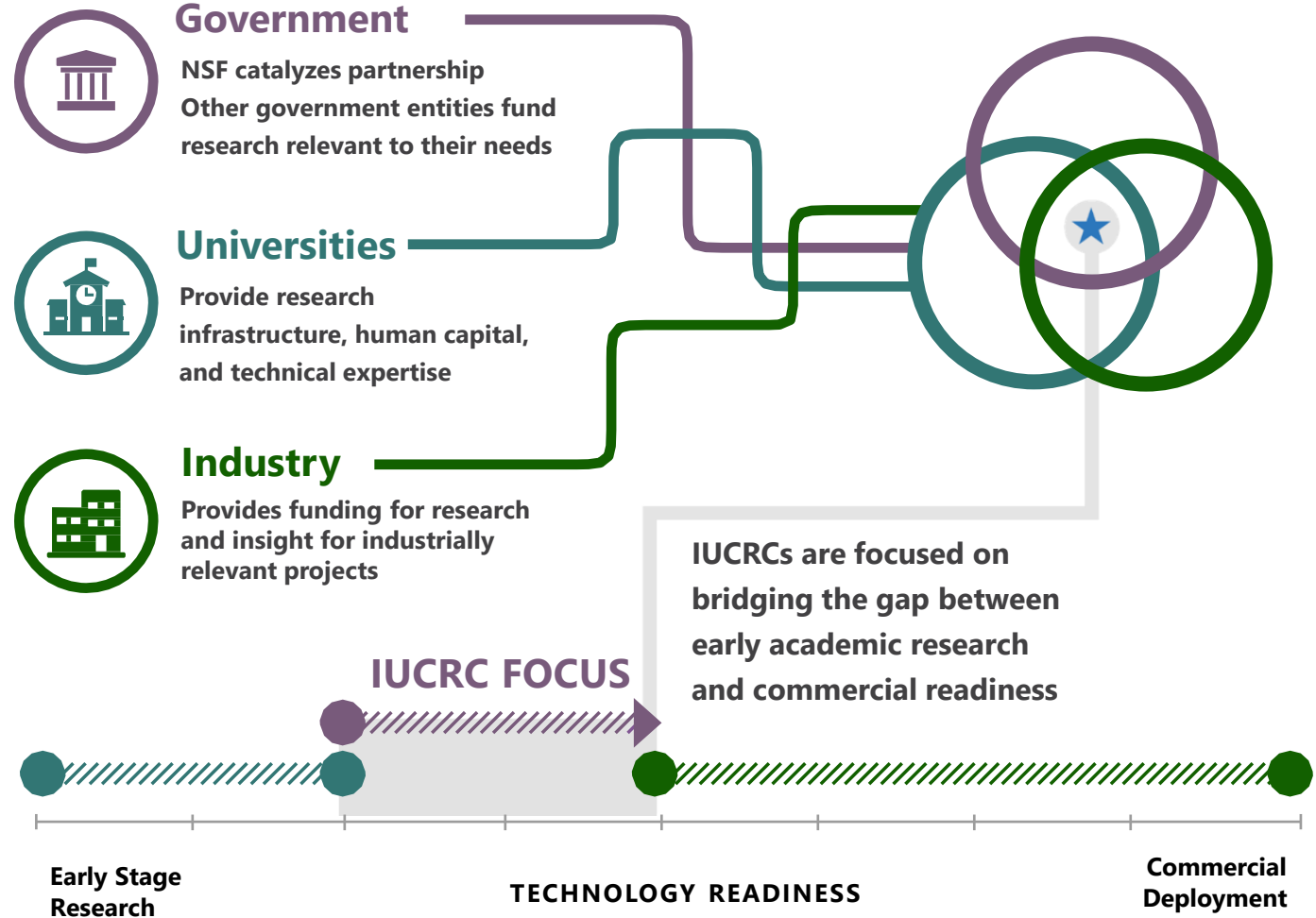
NSF

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**

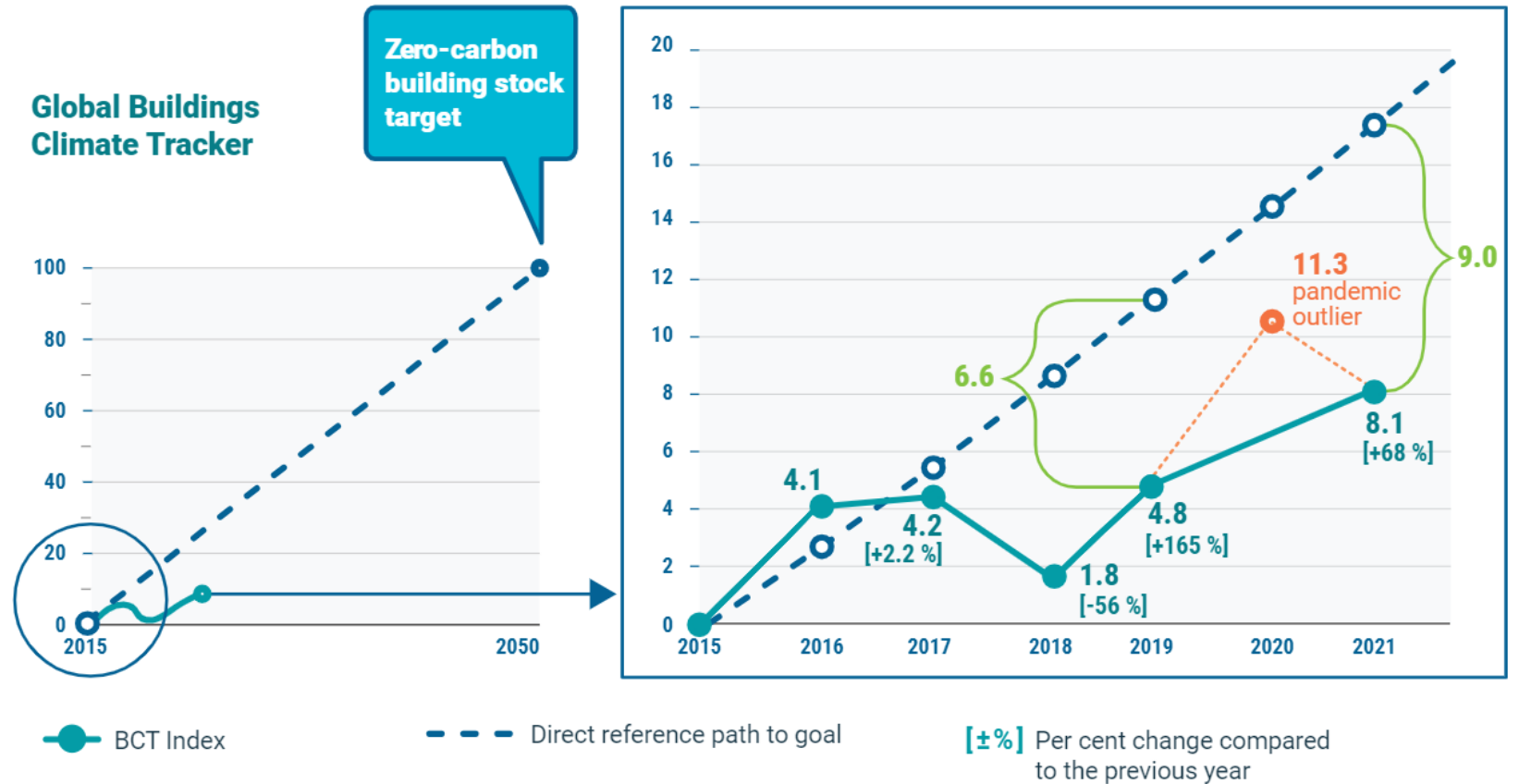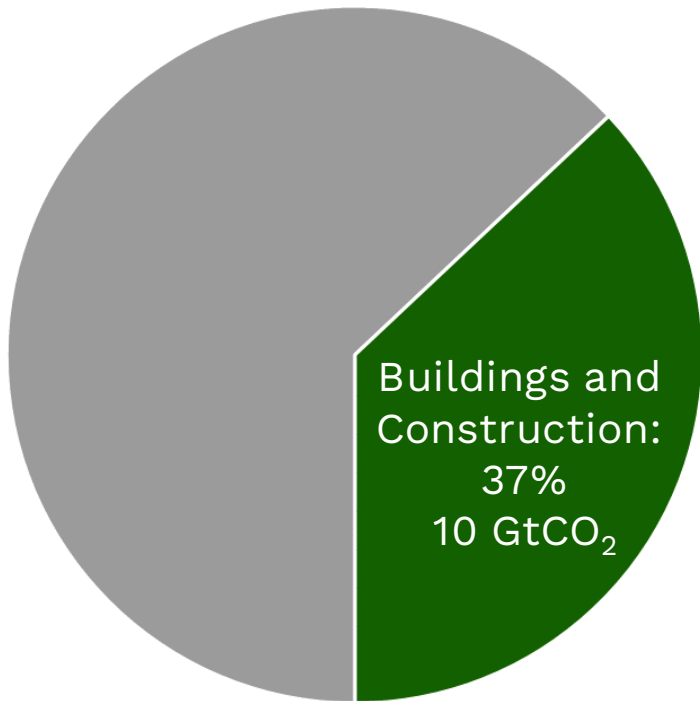**Industry advisory board (IAB) member fees fund research, education, and training activities**

## 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

6.6

9.0

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

2022 UN Global Status Report for Buildings and Construction

# 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 | Winter: Proposal Preparation | Spring: IAB Meeting | Summer: Research Funding Awarded |
|---|---|---|---|
| Faculty & IAB establish annual research topics | Faculty prepare proposals<br><br>IAB reviews proposals | Faculty/students present proposals & research results<br><br>IAB makes funding recommendations | Funding is awarded to funded project PIs & research projects start |

# What sets BEST apart from other building-related university research efforts?

The BEST Center brings industries together to learn from each other and conduct *interdisciplinary* research that benefits the whole building industry.
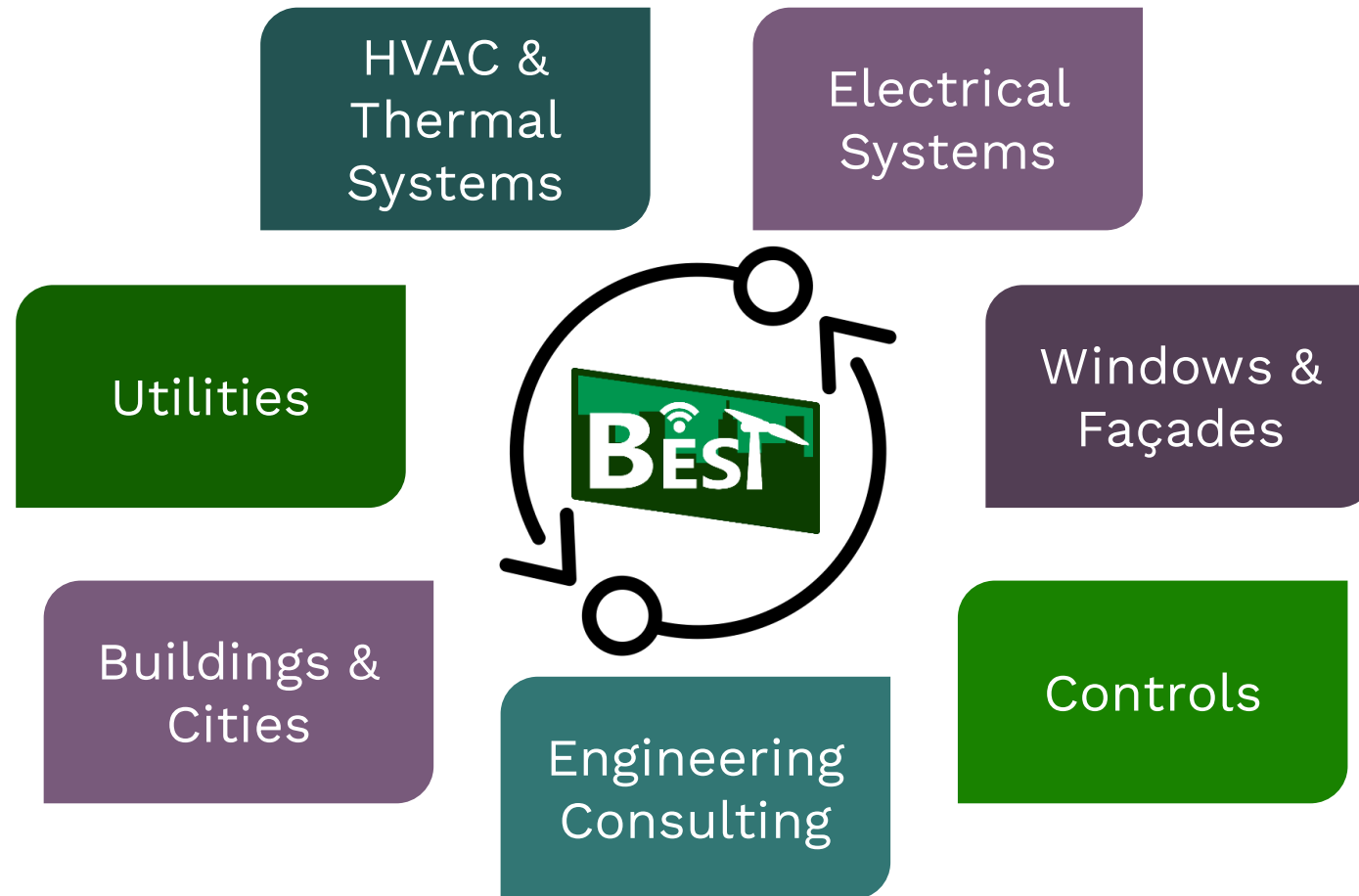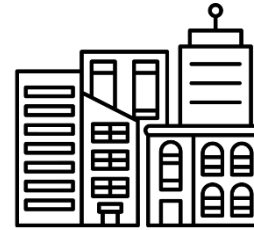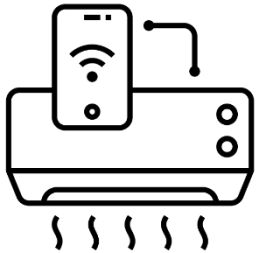
# BEST Center Research Themes
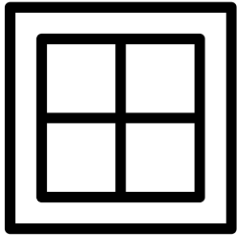
### Innovative Building Materials
Dynamically adaptive building shells and envelope systems adjust to changes in indoor and outdoor environments and effectively meet structural & efficiency requirements.
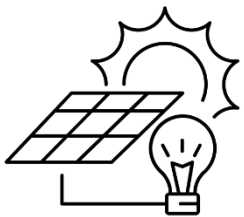
### Advanced Energy Systems
Enhance the energy efficiency of various building systems and equipment to meet occupants' comfort and health needs and increase their productivity.

### Integrated Energy Generation & Storage Systems
Such systems include solar power integrated into building envelopes, combined heat and power systems, and thermo-electric generators.

### Smart Buildings & Cities
Integrate energy efficiency technologies, advanced controls, and renewable energy resources to improve building and city design and operation.
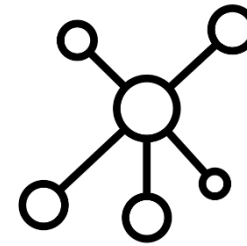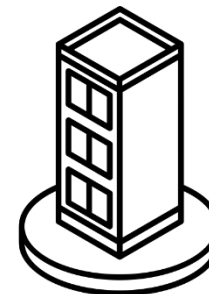
### Intelligent Grid Systems
Operate an increasing number of distributed energy resources to exchange optimally and efficiently energy between the electric grid and buildings.

### 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



University of Colorado Boulder

The City College of New York

Innovative Building Materials

Integrated Energy Generation & Storage Systems

Smart Buildings & Cities

Building Retrofit Applications

Intelligent Grid Systems

Advanced Energy Systems
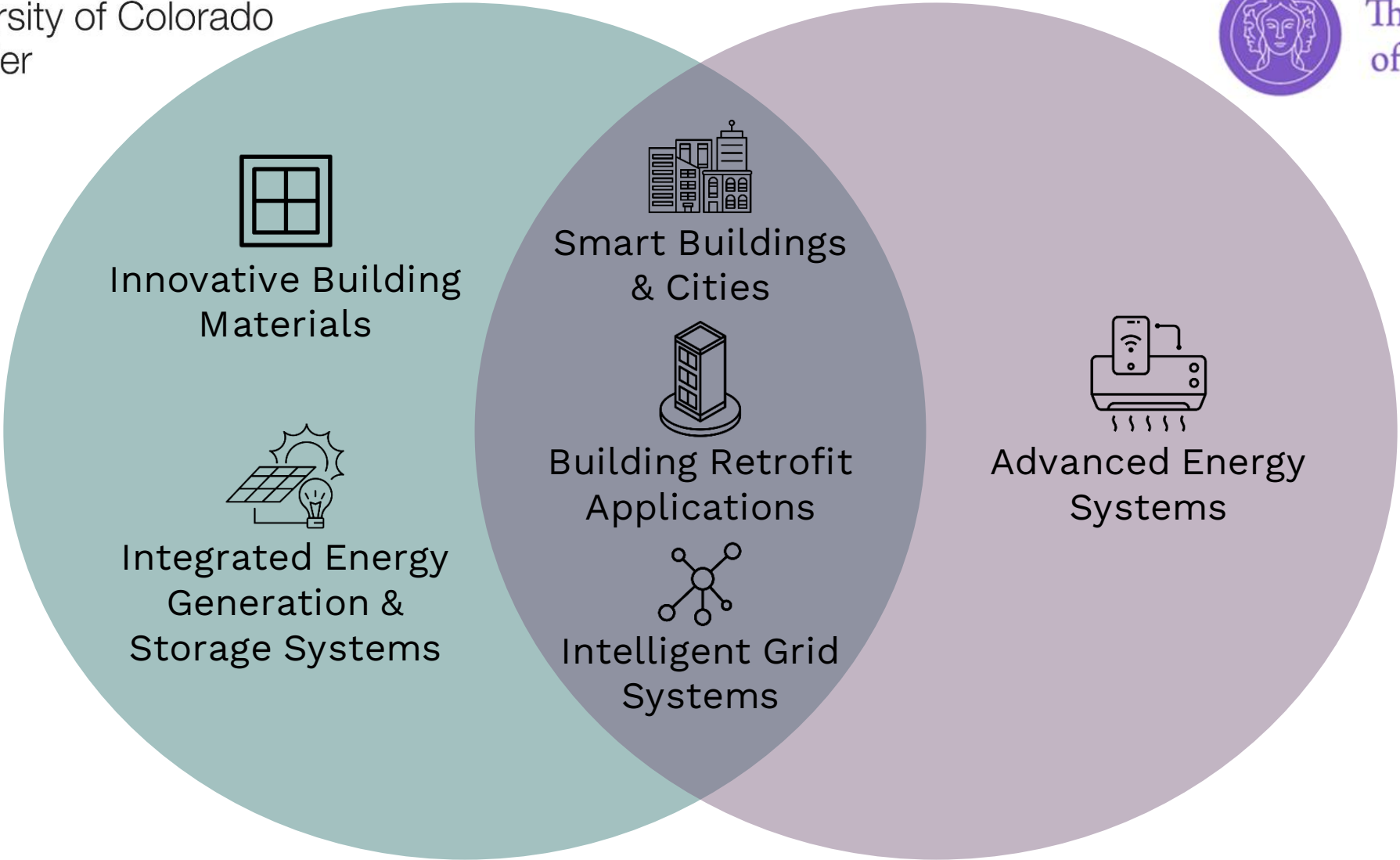
# BEST Center Funded Research 2024-2025



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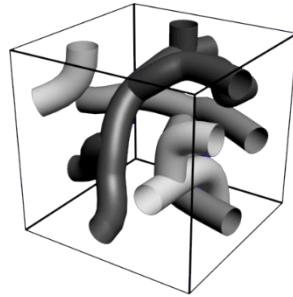
Design & Techno-Economic Assessment Tool for ASHP Systems for Cooling, Heating and Hot Water
Ramamurthy (CCNY), Gonzalez-Cruz (UAlbany)

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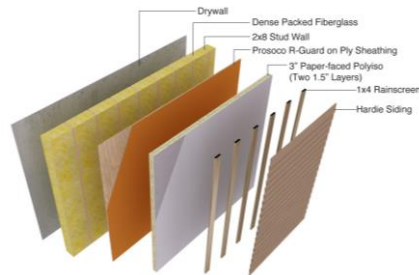
Performance Evaluation and Grid Impacts of Intelligent Field Devices and Next-Generation Heat Pumps with an Application to Adaptive Reuse of Commercial Buildings
Henze (CU)
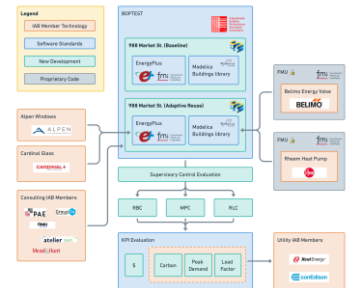
Feasibility Evaluation of Net-Positive Window Systems
Krarti (CU), McGehee (CU)

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, 2024-2026
Silvia Khurrum
Con Edison

IAB Vice Chair, 2024-2026
Ati Manay
Rheem

# Industry Advisory Board Members

## Full Members (5 votes, 1 vote/member)

Rheem

Xcel Energy®

EAT•N

conEdison

CARDINAL Glass Industries

## Associate Members
### (1.5 votes, 0.5 vote/member)

ALPEN HIGH PERFORMANCE PRODUCTS

BELIMO®

RMH GROUP

## Affiliates

Group 14 ENGINEERING

atelier ten

Western Mechanical Solutions SUSTAINABLE HEATING COOLING

Mead&Hunt

PAE

CITY OF BOULDER

# 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 | ✓ | ✓ | ✓ |

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-$CO_2$) 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.
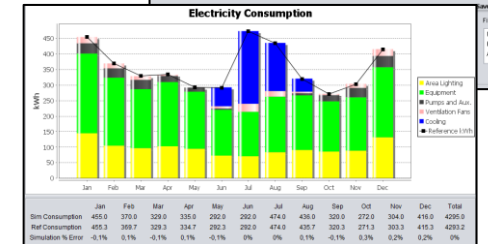


**Evaluation of Field Methods for Assessment of Architectural Window Degradation**
PIs: Zhai (CU), Tenent (NREL)

- 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
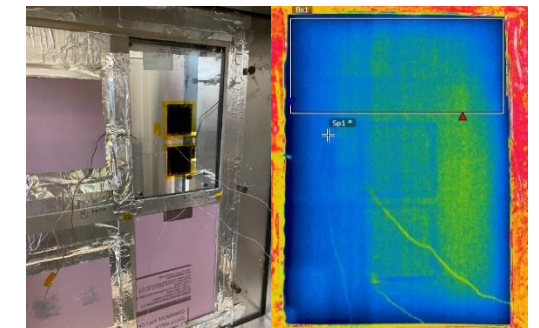
# BEST Center Funded Research 2023-2024

**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
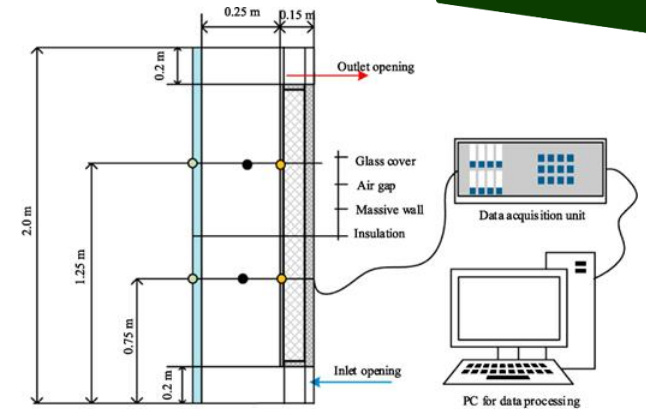


**Evaluation of Hygrothermal and Energy Efficiency and Condensation Risk of Secondary Windows**
PIs: Zhai (CU), Tenent, Kiatreungwattana (NREL)

- 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.
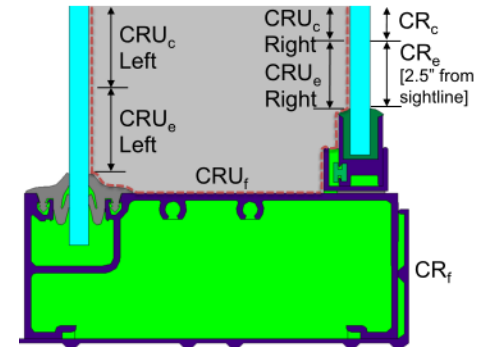


**6. Making Reinforcement Learning Practical for Building Control through Human Feedback**
PI: Gregor Henze (CU)

- 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.
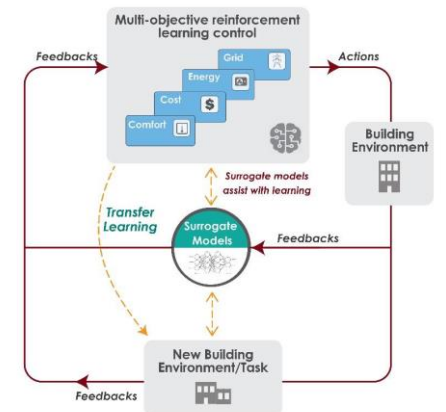
# BEST Center Funded Research 2022-2023

**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
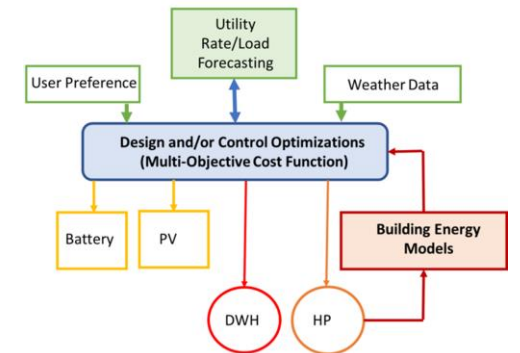


**Energy-Reduction M&V using Calibrated Simulation (IPMVP Option D)**
PIs: Berk, Prahl (CCNY)

- 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
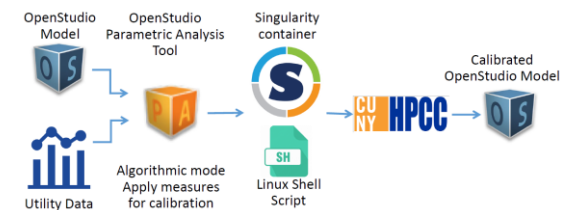
# BEST Center Funded Research 2022-2023

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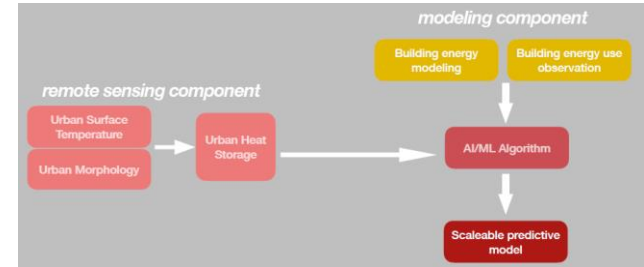
### Flexible Insulated Panels for Retrofitting Existing Building Envelopes
### PIs: Krarti, Roudbari (CU)

- 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
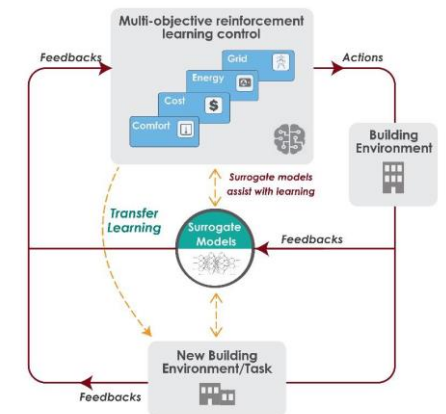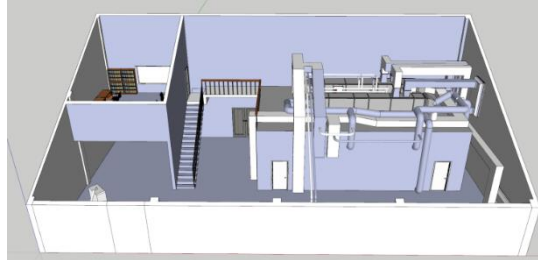
# CU Boulder Research Capabilities

## 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
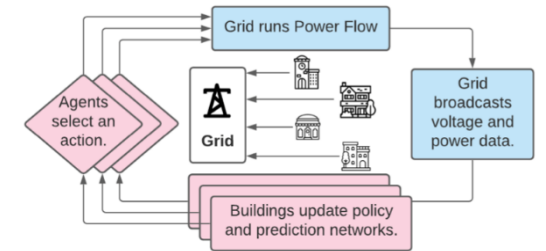


## Lighting Lab
### (Vasconez, Scheib)

- 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
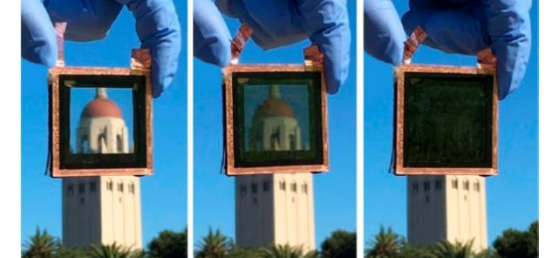


## Living Materials Lab
### (Srubar)

- 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
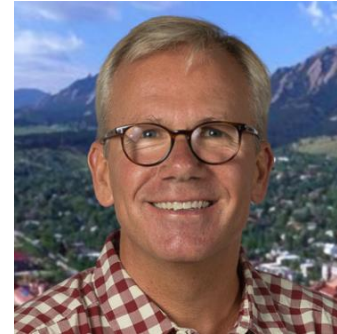- Nanoscience for energy capture and conversion
- RASEI Website

# 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
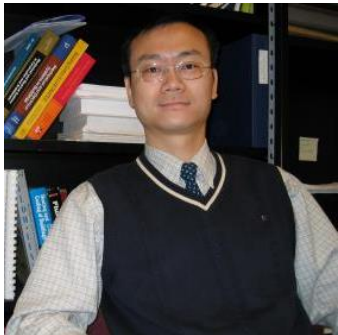
### Prof. John Zhai
- Computational fluid dynamics in buildings
- Thermal comfort & indoor air quality
- HVAC systems & heat transfer
- Building vulnerability & safety
- Renewable energy & sustainable building design

### 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
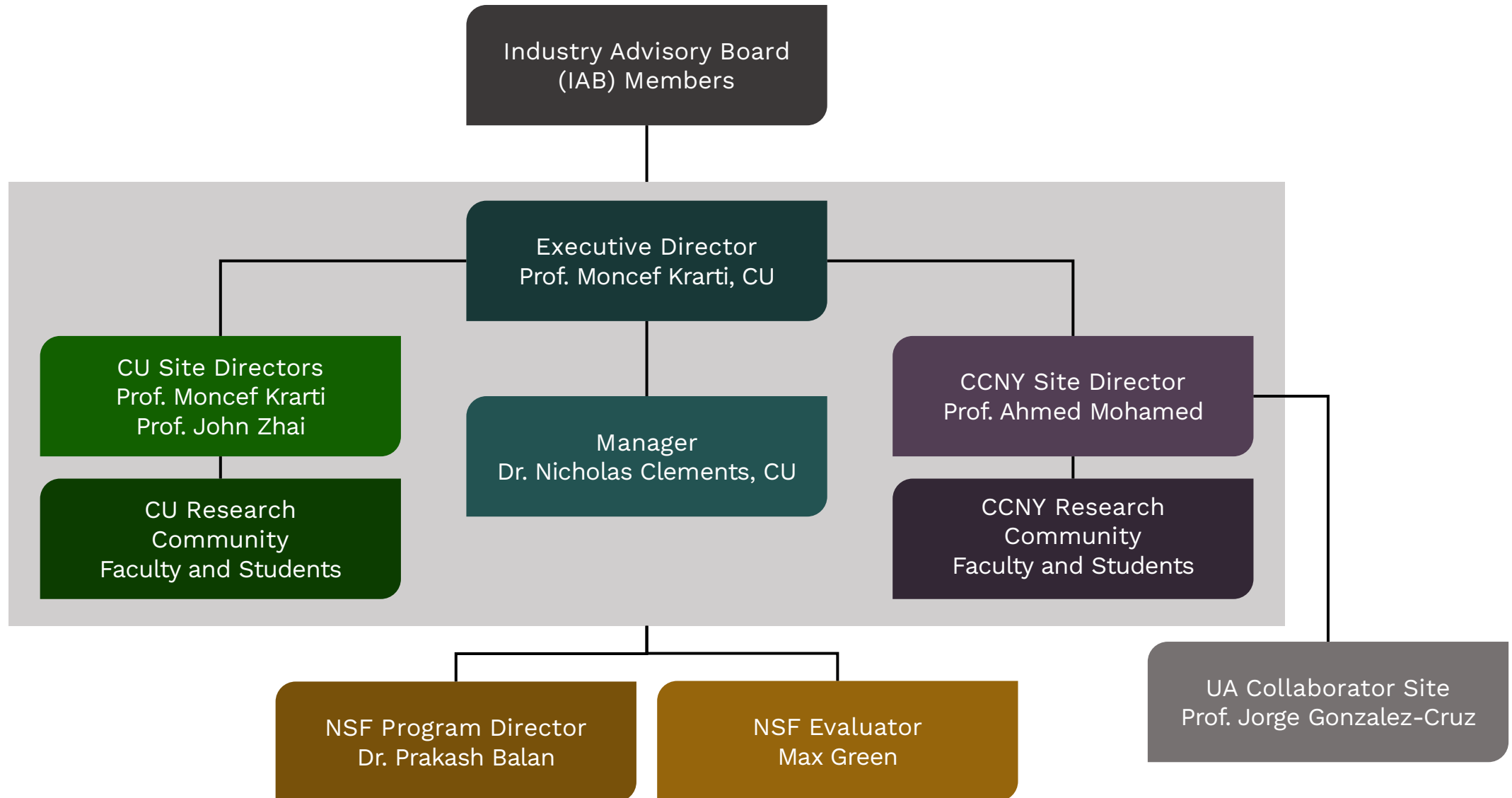
### Michael Bobker
- Director, Building Performance Lab

### 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

# BEST Center Research Highlight:
## Retrofit Analysis Tool

# BEST Center Research Highlight:
# Trans-critical $CO_2$ Heat Pump Development