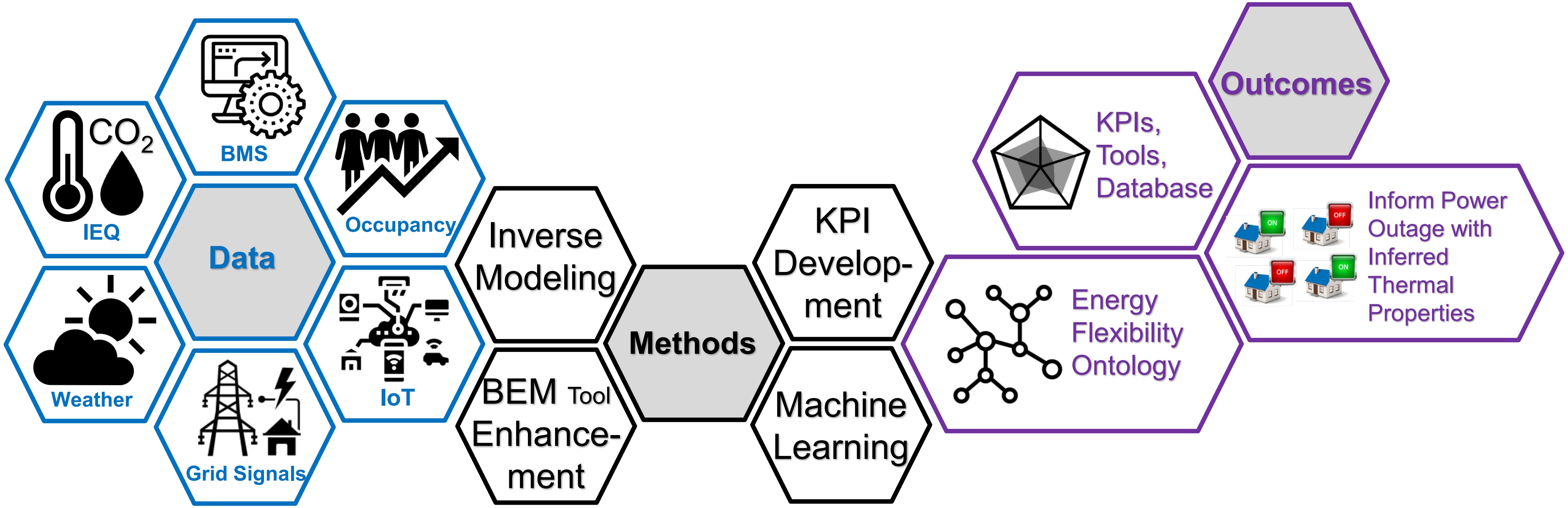
Sensor Data Integration



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Project Summary

Timeline:

Start date: October 1, 2019 (FY20)

Planned end date: September 30, 2022 (FY22)

Key Milestones

1. Developed a suite of occupant KPIs and release of an OpenStudio reporting measure (FY20 Q4)
2. Developed a novel method to infer residential building thermal dynamics for informing power outage planning (FY21 Q2)
3. Reviewed methods and metrics for energy flexibility characterization and quantification in residential buildings; a journal article published. (FY21 Q3)

Budget:

Total Project $ to Date:

- DOE: $410k
- Cost Share: N/A

Total Project $:

- DOE: $750k
- Cost Share: N/A

Key Partners:

ecobee	ASHRAE
ALLIANCE TO SAVE ENERGY using less. doing more.	EBC Energy in Building and Communities Programme

Project Outcome:

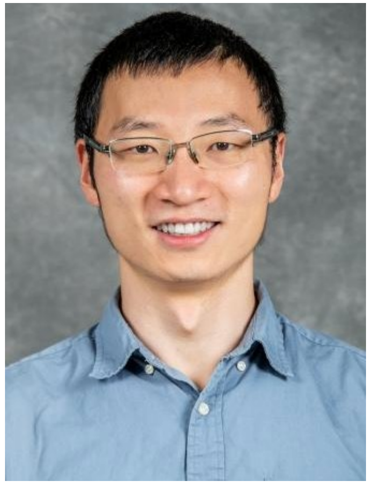
The project focuses on development and applications of new methods to analyze sensor and meter data for improving building performance modeling and evaluation:

- System level and occupant KPIs for deeper performance analysis
- Inverse modeling for thermal resilience analysis
- An ontology to represent energy flexibility supporting GEB modeling and evaluation

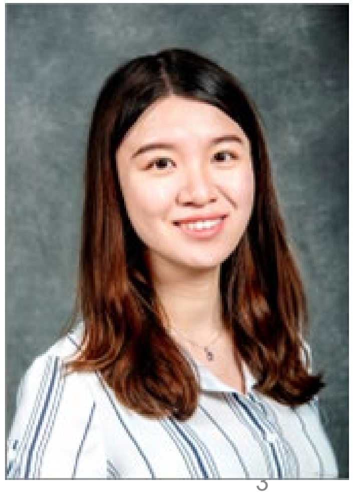
Team

Tianzhen Hong, PhD
Senior Scientist
PI, LBNL

Han Li
Project Engineer
LBNL



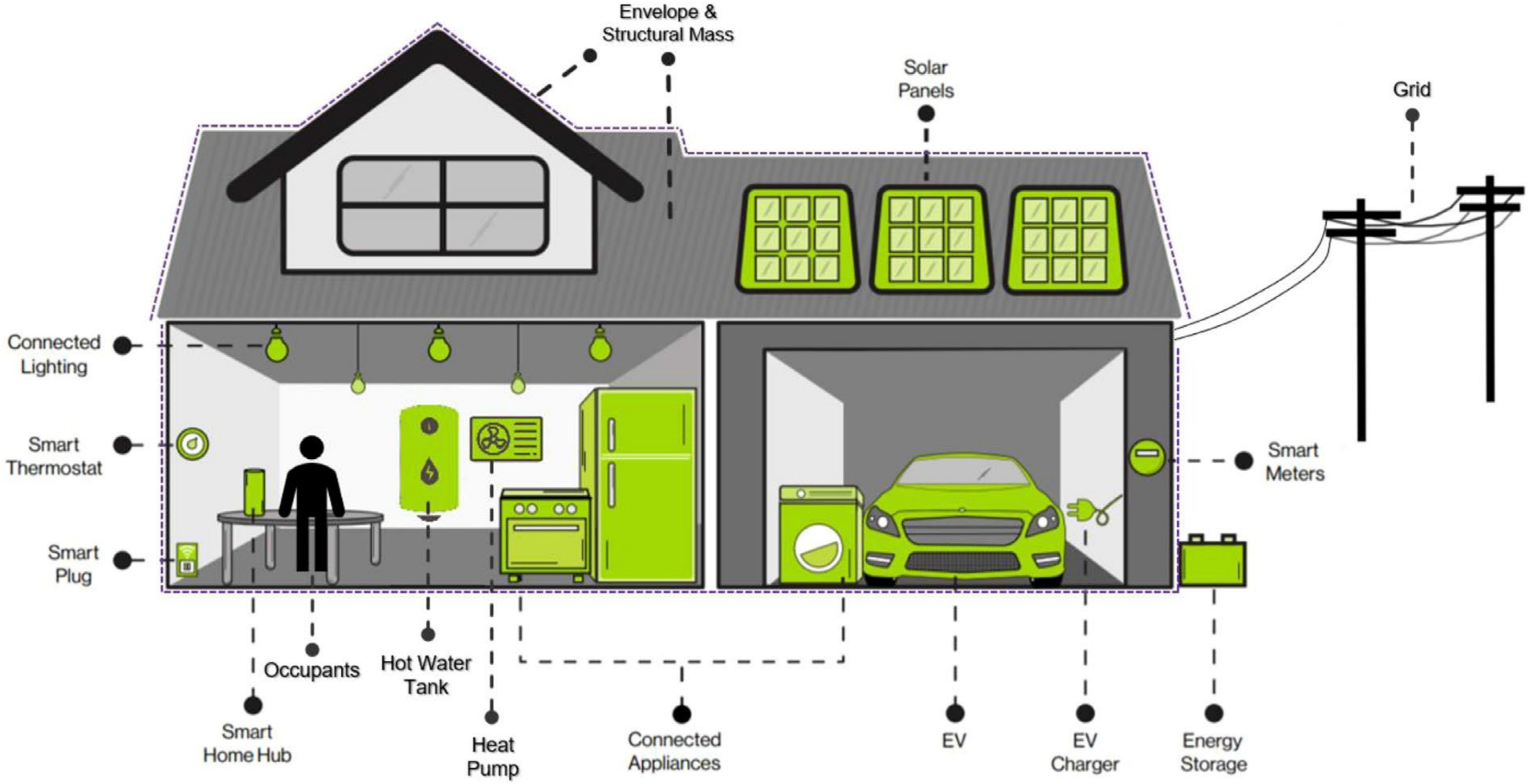
Zhe Wang, PhD
Project Scientist
LBNL



Xuan Luo
EnergyPlus Developer
LBNL

Challenges

- Building operations are becoming much more complex to optimize performance for energy efficiency, demand flexibility, and thermal resilience due to the increasing dynamic demand and supply
- Sensors and meters in buildings and IoT devices are producing a large volume of data
- Unlocking values and extracting insights from data is a huge but challenging opportunity



Approaches

The project aims to develop novel methods and metrics to analyze sensor and meter data for improving building energy modeling and performance evaluation of grid-interactive efficient buildings (GEBs):

- Energy efficiency and occupant comfort
  - Develop system-level KPIs, an OpenStudio reporting measure, and a database from prototype building model simulations
  - Develop occupant-centric KPIs and an OpenStudio reporting measure
- Thermal resilience
  - Integrate advanced analytics with inverse modeling to analyze the Ecobee dataset to inform thermal resilience of buildings
- Energy flexibility
  - Develop an ontology of energy flexibility of buildings
  - Conduct a case study using data-driven methods to quantify energy flexibility of residential buildings

Impacts

- The system-level KPIs enable deeper building energy performance analysis, benchmarking, and diagnostics.
- The occupant KPIs enable multi-domain analysis of building services (IEQ), human-building interactions, and resources use and environmental impacts.
- The Ecobee dataset analysis demonstrated a use case of advanced analytics to inform thermal resilience of buildings by estimating maximum safe duration of rotating power outages during heatwaves.
- The ontology for energy flexibility enables standard representation of flexible resources and loads in buildings improving GEB technologies modeling and evaluation.

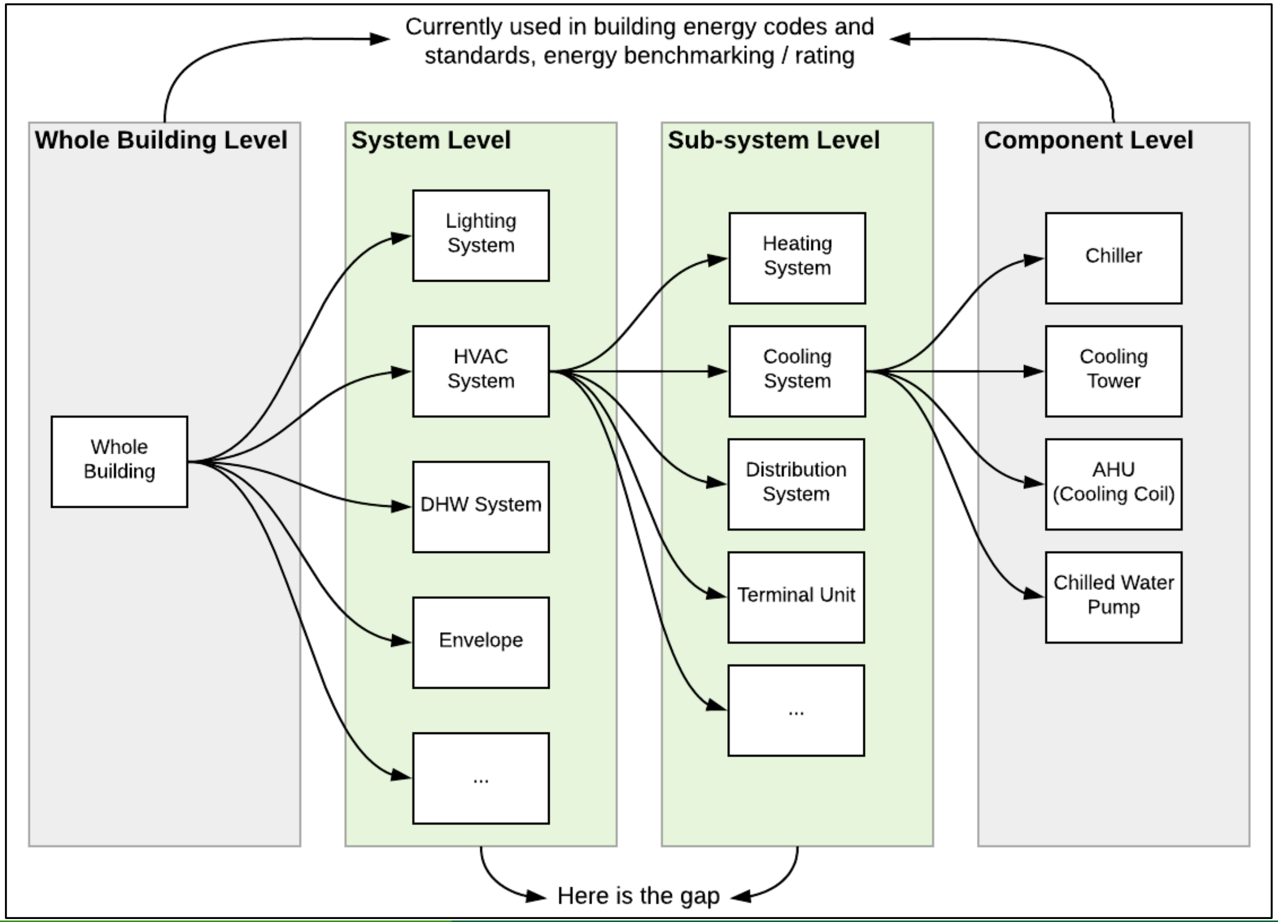
The BTO Sensors and Controls Sub-Program website acknowledges the role of advanced analytics and interoperability for energy flexibility:

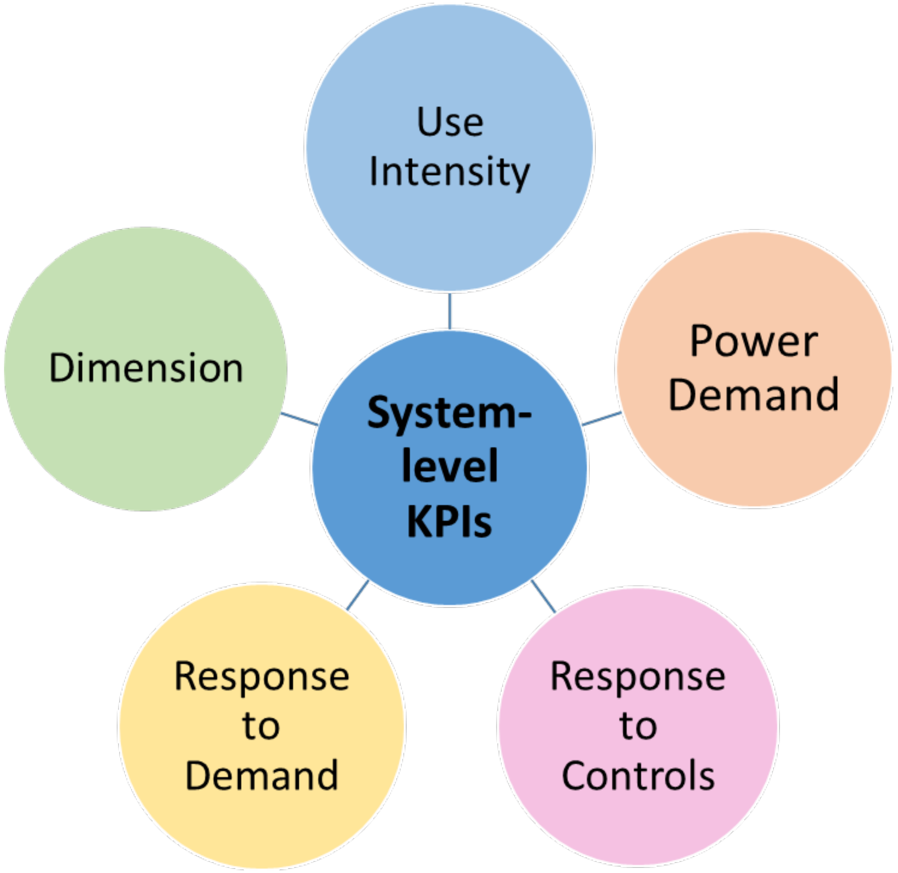
"To complement the portfolio of competitive and interdisciplinary, early-stage R&D projects, testing frameworks and procedures, along with curated datasets are being developed by the sub-program to support the R&D community at-large through common baselines to evaluate performance improvements and encourage additional innovation in ***advanced analytics*** *and control strategies. Advancements in* ***interoperability*** *are also being explored to complement stakeholder-led communication protocol, data tagging and modeling developments underway. Finally, the technological advancements made by the sub-program are being leveraged to inform BTO investments in transactive control methods for* ***flexible building loads****."*

Progress: FY20 - System-level KPIs

Development of System-level KPIs:

- The system-level KPIs aim to fill the gap of missing performance evaluation at system-level
- A suite of 43 KPIs across four system categories and 12 sub-system categories were developed
- The KPIs cover more granular performance aspects than traditional whole-building performance metrics

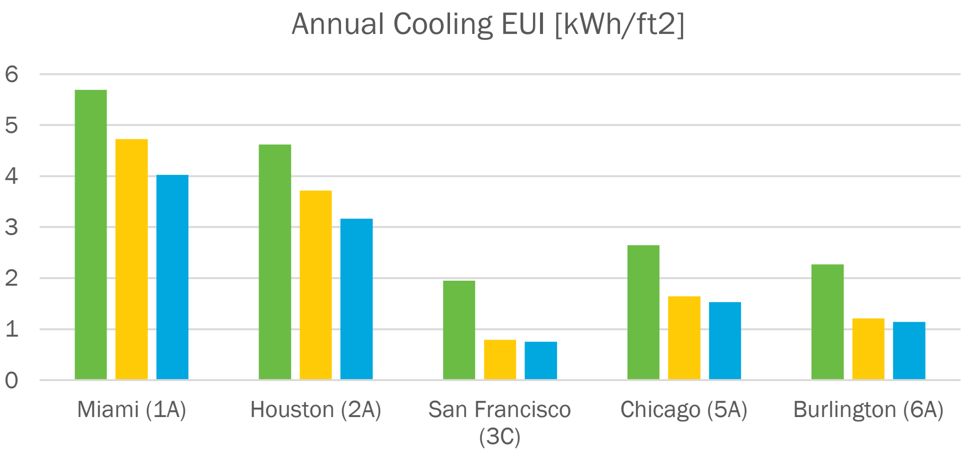


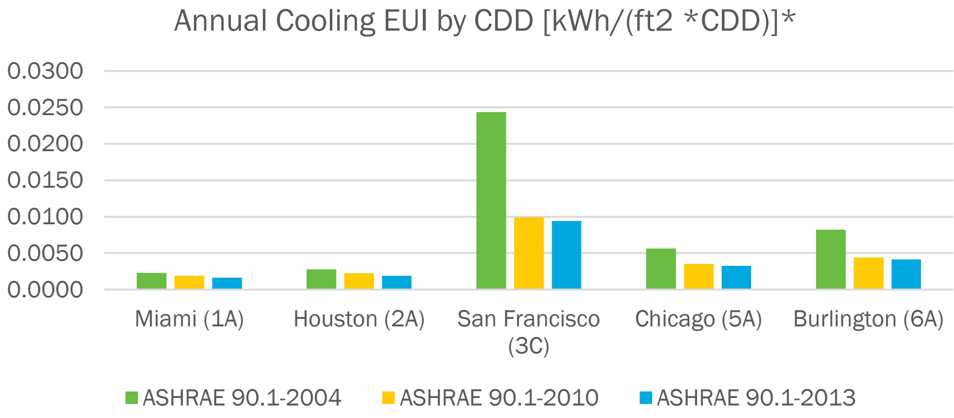


Progress: FY20 - System-level KPIs

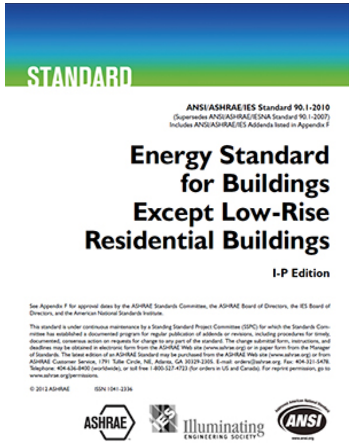
Applications of system-level KPIs

1. Enables building performance evaluations from different perspectives of interest

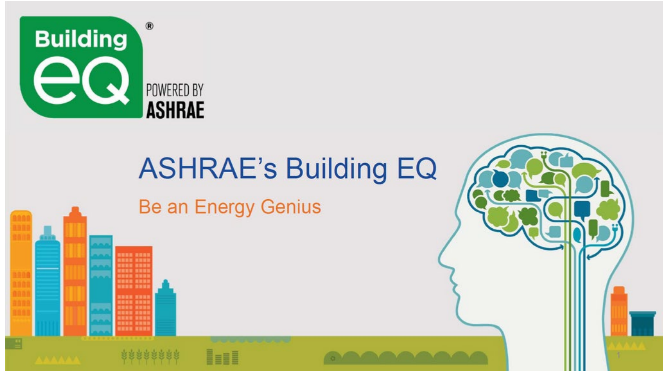




2. Provides a potential new system performance compliance path in building codes and standards (e.g., 90.1, 189.1)



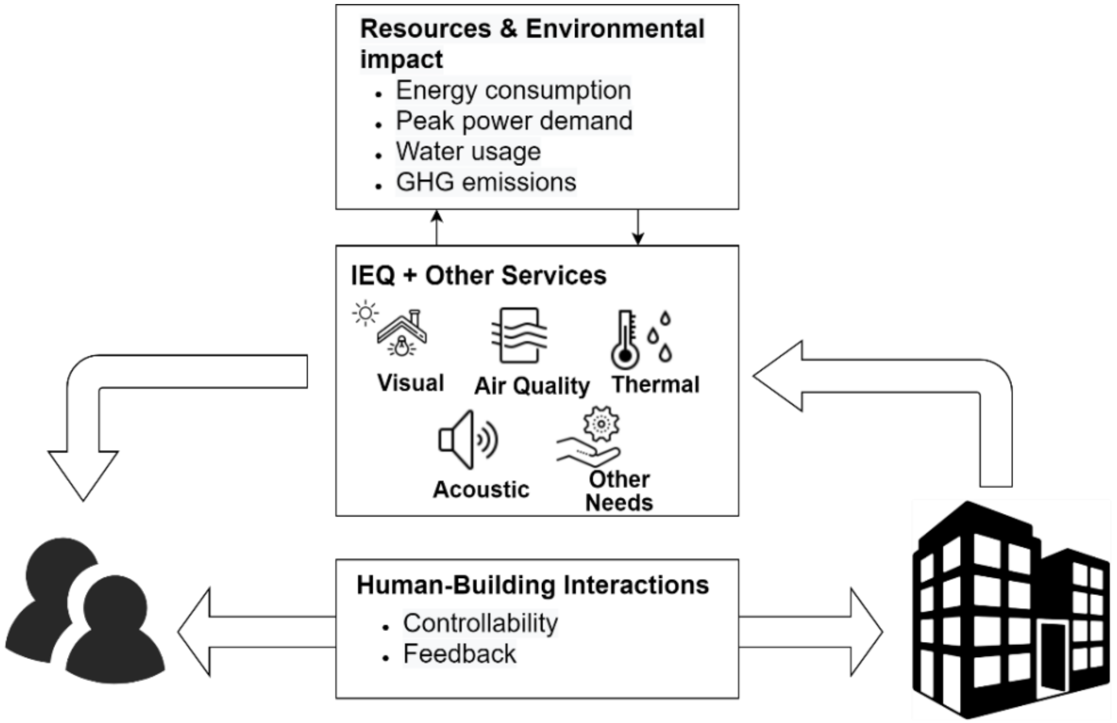
3. Supports building performance tracking and benchmarking (e.g., ASHRAE bEQ tools, BAS)

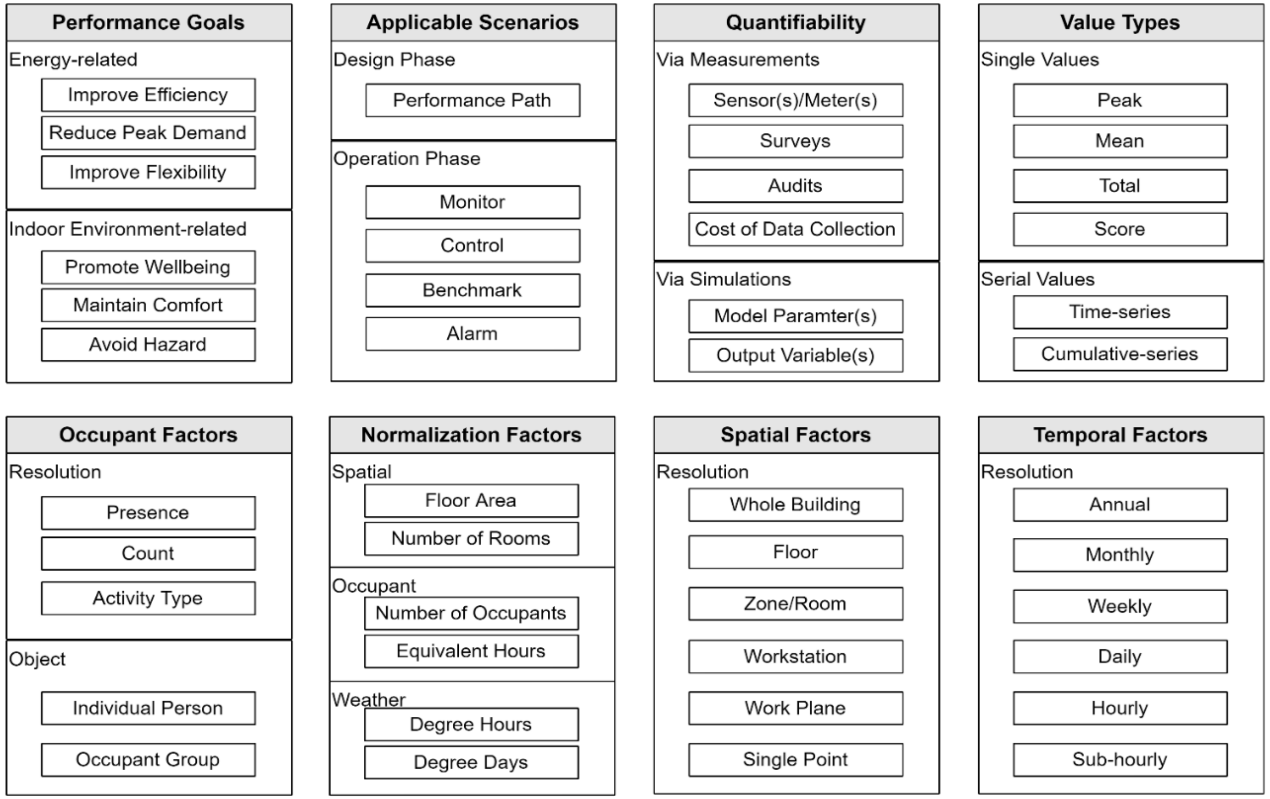


Progress: FY20 - Occupant-centric KPIs

Review and Synthesis of Occupant-centric KPIs

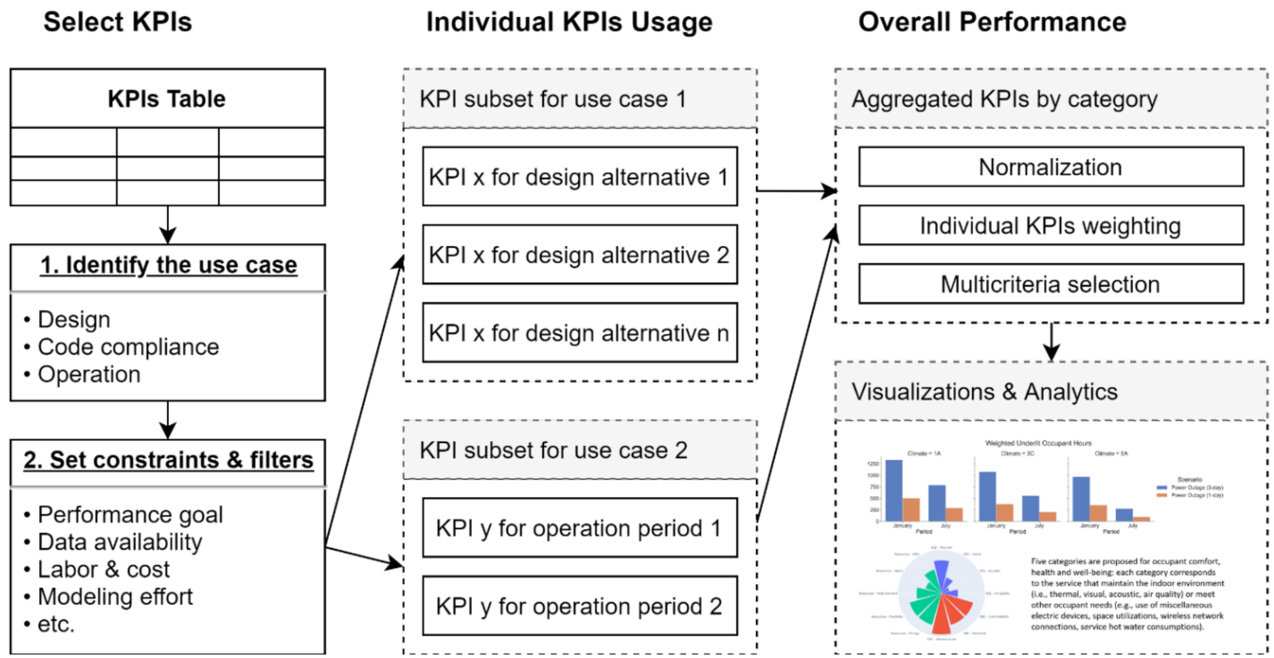
- Investigated building performance evaluation leveraging increasingly available occupant-related data
- Developed a building performance evaluation framework from occupant-centric perspective
- Summarized key considerations for occupant-centric KPIs
- Developed an OpenStudio reporting measure





Progress: FY20 - Occupant-centric KPIs

Applications of occupant-centric KPIs – compare different design alternatives



Single-value KPIs

Fanger Comfort Model

Zone	Area (m^2)	Average Negative PMV (when occupied)	Average Positive PMV (when occupied)	Annual Average PPD (when occupied) (%)	Annual Exceedance hours (when occupied and PPD>20%) (hours)	Annual Overcooling Degree-hours* (°C*hour)	Annual Overheating Degree-hours* (°C*hour)
CORNER_CLASS_2_POD_3_ZN_1_FLR_1 ZN	99.0	-0.58	0.45	11.3	141.3	0.0	15.2
LIBRARY_MEDIA_CENTER_ZN_1_FLR_1 ZN	399.0	-0.52	0.43	10.3	58.0	0.0	45.3
GYM_ZN_1_FLR_1 ZN	357.0	-0.52	0.56	11.7	35.5	0.0	472.2
MULT_CLASS_1_POD_3_ZN_1_FLR_1 ZN	477.0	-0.42	0.47	10.2	51.5	0.0	483.6
KITCHEN_ZN_1_FLR_1 ZN	168.0	-0.24	0.67	13.5	700.3	0.0	3140.2
CORNER_CLASS_1_POD_2_ZN_1_FLR_1 ZN	99.0	-0.54	0.5	11.5	120.5	0.0	212.0
MULT_CLASS_1_POD_1_ZN_1_FLR_1 ZN	477.0	-0.42	0.48	10.4	86.8	0.0	510.3
MULT_CLASS_2_POD_2_ZN_1_FLR_1 ZN	477.0	-0.47	0.41	9.7	51.0	0.0	52.4

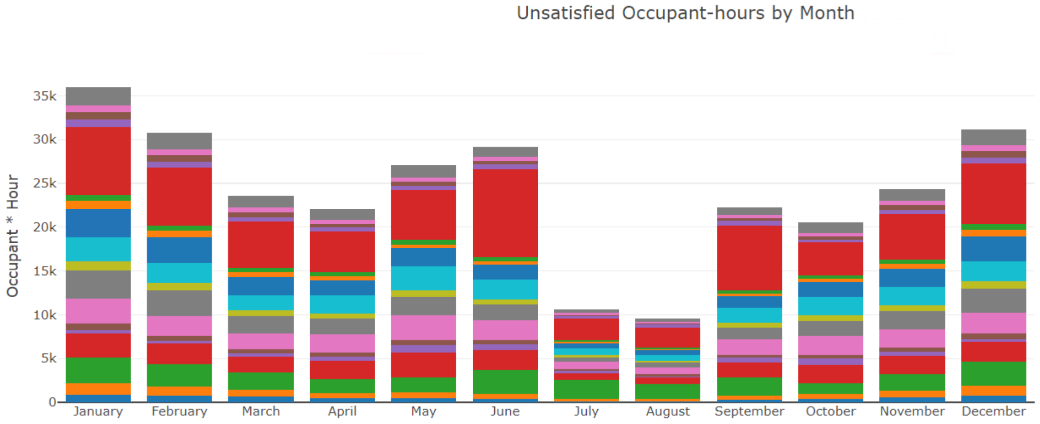


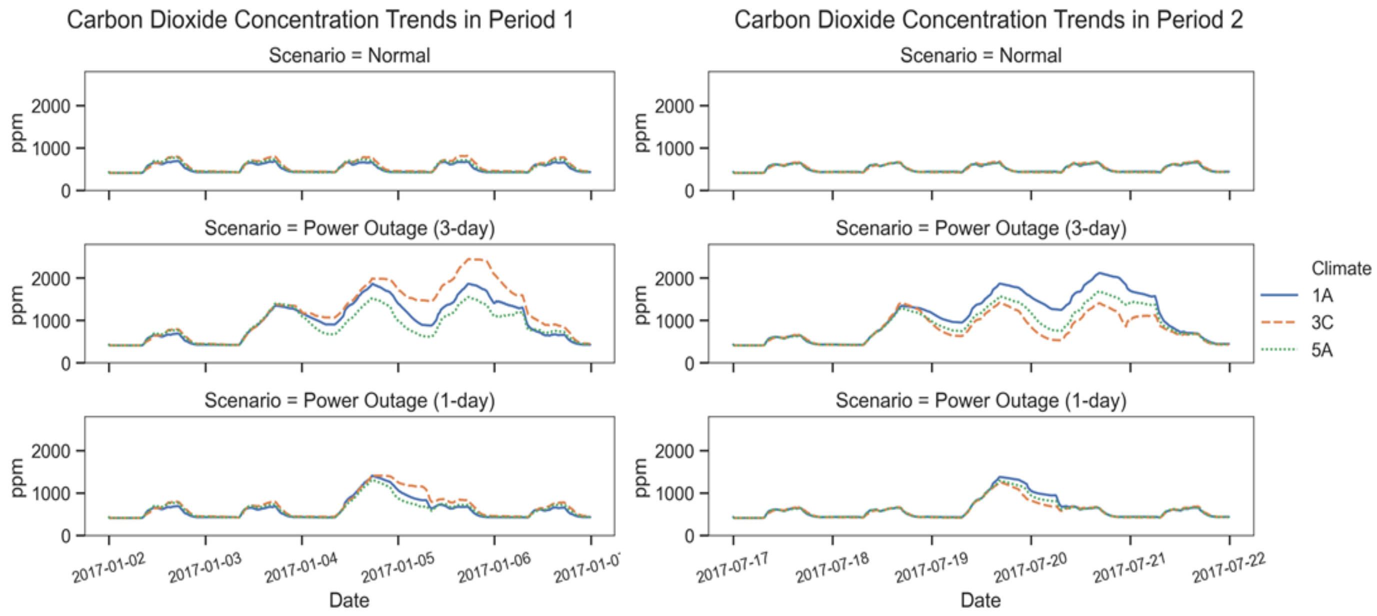
Image shows an KPI report automatically generated with an OpenStudio measure

Progress: FY20 - Occupant-centric KPIs

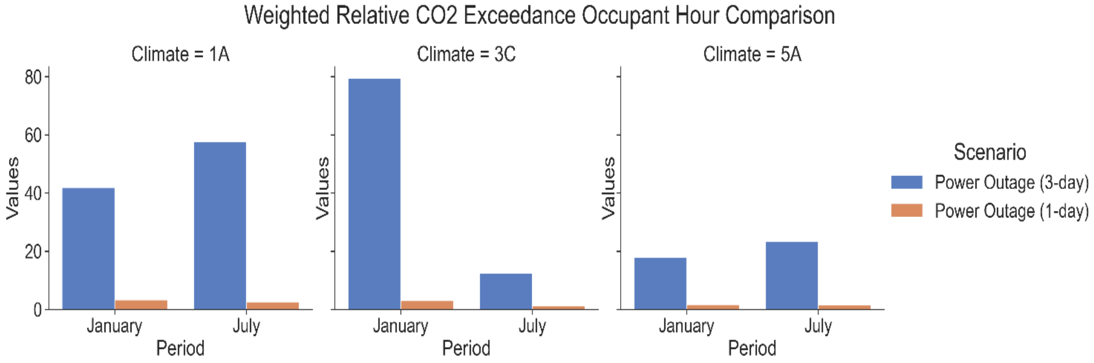
Applications of occupant-centric KPIs - performance tracking from occupant-centric perspectives

Example shows the use of a KPI to evaluate the influence of power outage considering the number of occupants and the rise of CO_2 concentration due to lack of ventilation.

CO_2 measurements do not quantify the impacts



KPIs evaluate the degree of impacts



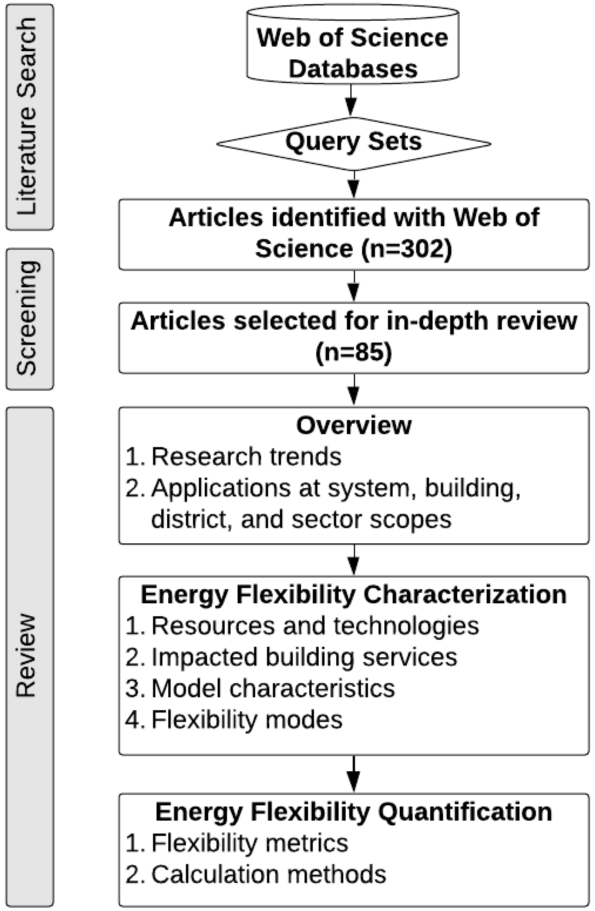
$$Weighted\ Total(CO_2\ Exceedance) = \sum \frac{CO_{2,i} - CO_{2,refernce}}{CO_{2,refernce}} \cdot nOcc_i \cdot W_i\ ,$$

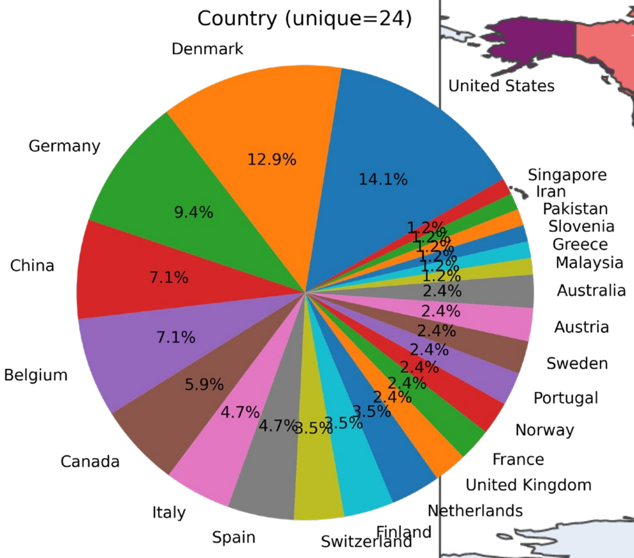
$$W_i = \begin{cases} 0, & CO_{2,i} < CO_{2,refernce} \\ 1, & CO_{2,refernce} < CO_{2,i} \le CO_{2,threshold\_1} \\ 5, & CO_{2,i} > CO_{2,threshold\_1} \end{cases}$$

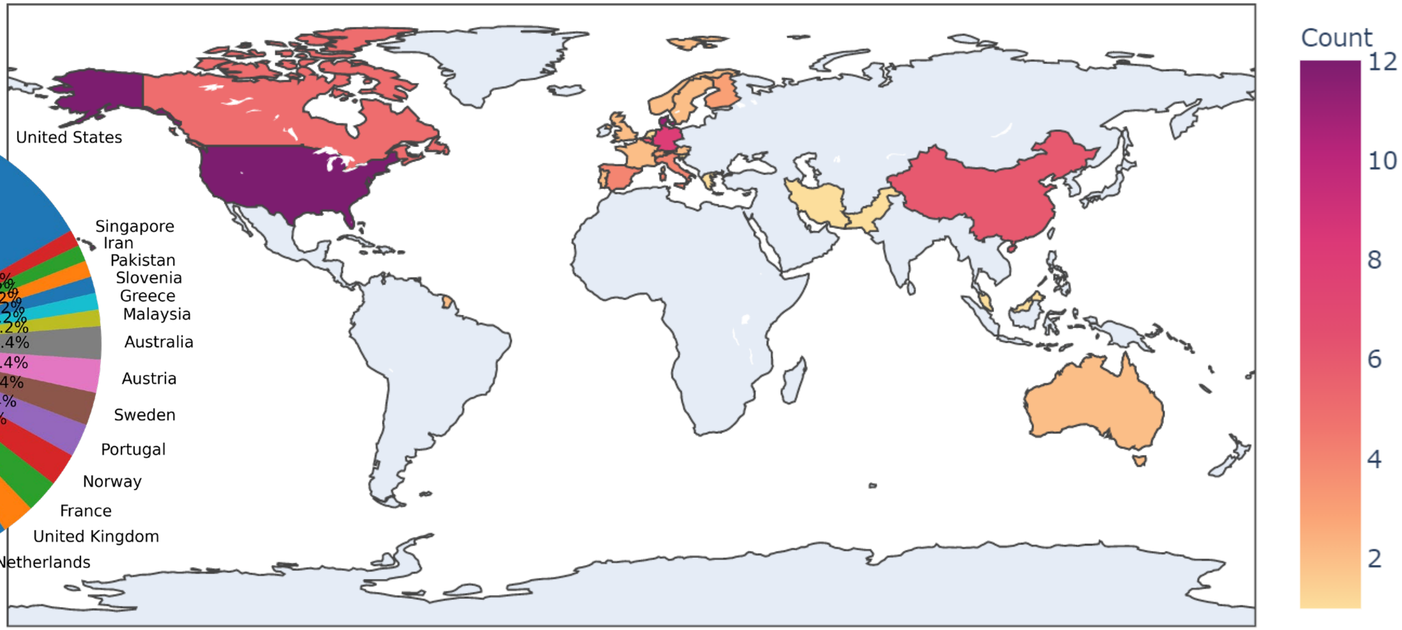
Outdoor CO2 concentration = 400 ppm
Unhealthy CO2 concentration range = [1100ppm, 5000ppm)
Dangerous CO2 concentration limit = 5000ppm

Progress: FY21 - A Review on Building Energy Flexibility Characterization and Quantification Methods and Metrics

- Investigated energy flexibility quantification method and metrics using sensor/meter data and building energy modeling.
- Focused on how residential energy flexibility is achieved in different applications, and how it is described and quantified.
- 85 papers were selected from over 300 papers for in-depth review.

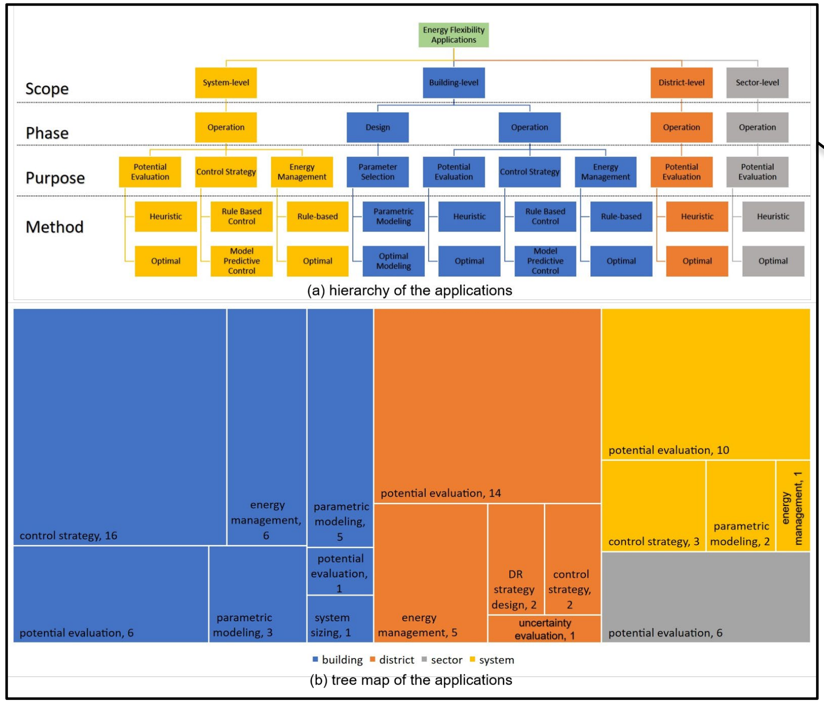






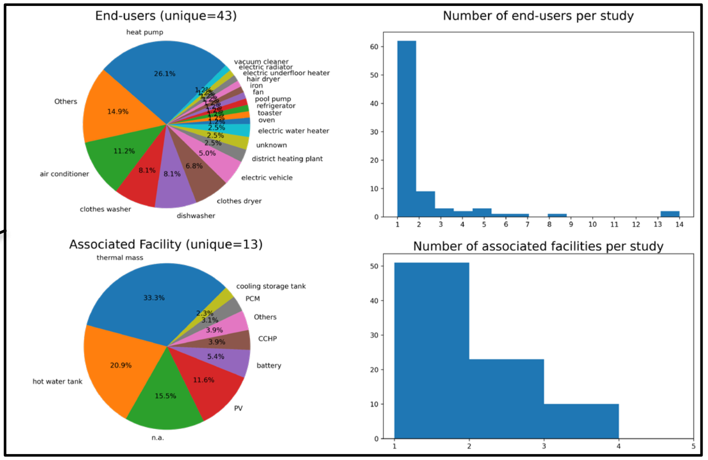
Progress: FY21 - A Review on Building Energy Flexibility Characterization and Quantification Methods and Metrics

Multi-scale Applications



Identified gaps in representing energy flexibility resources and characterizing flexible load profiles.

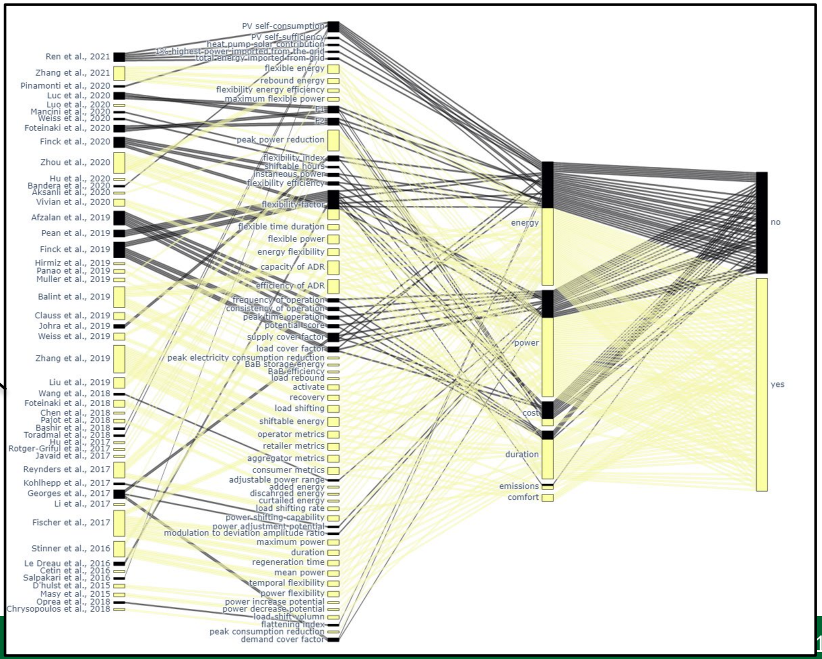
Energy Flexibility Resources



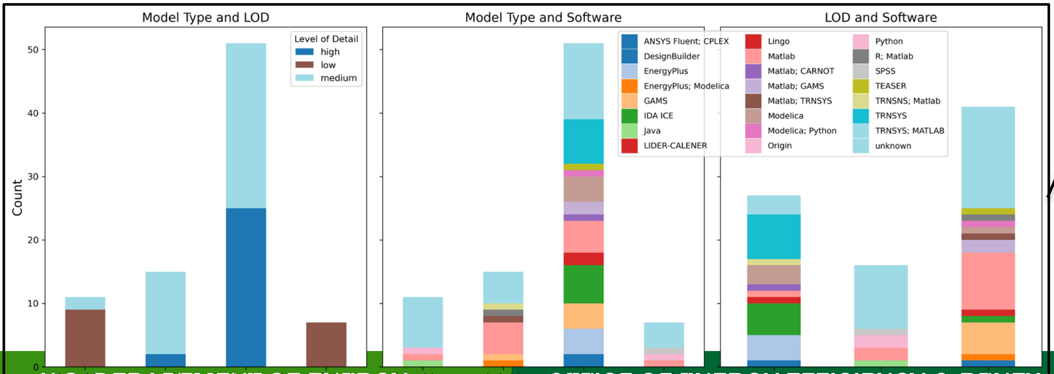
Research Gaps Identified:

- Lack of commonly agreed metrics to evaluate energy flexibility
- Lack of standardized representation of energy flexibility resources
- Lack of mechanism to define requirements, credit and incentivize energy flexibility

Energy Flexibility Quantification Metrics



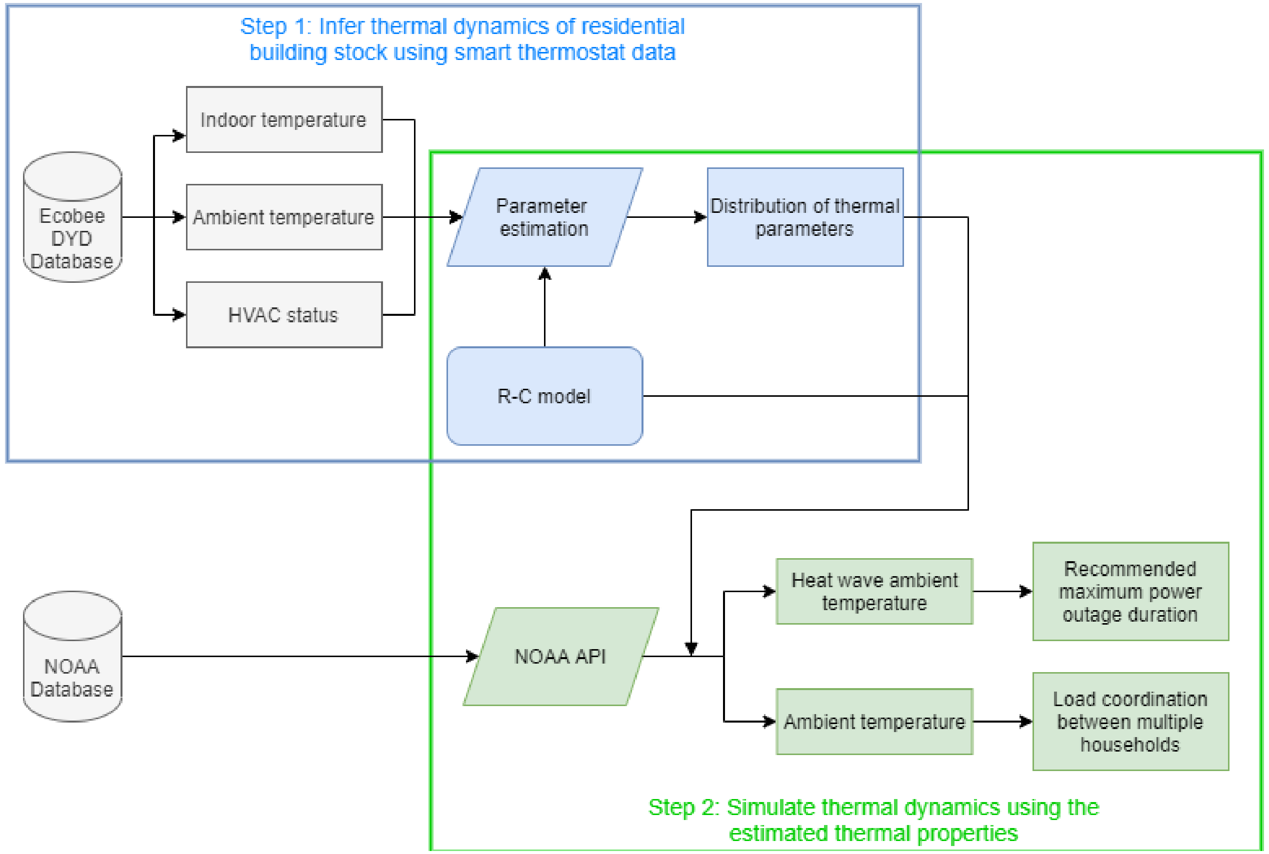
Energy Flexibility Modeling Techniques



Progress: FY21 - Infer building thermal properties

- Propose a new approach to infer residential building thermal properties using a *connected smart thermostat dataset*
- Inverse Modeling
  - *Same* structure, *different* parameters
  - Parameters to be inferred
    - R, C, T_{eq}; TTC = R*C
  - Find a period of time when
    - HVAC is off (free floating)
    - Indoor-outdoor heat transfer dominates
    - T_{eq} is constant or close to 0

* TTC: Thermal Time Constant



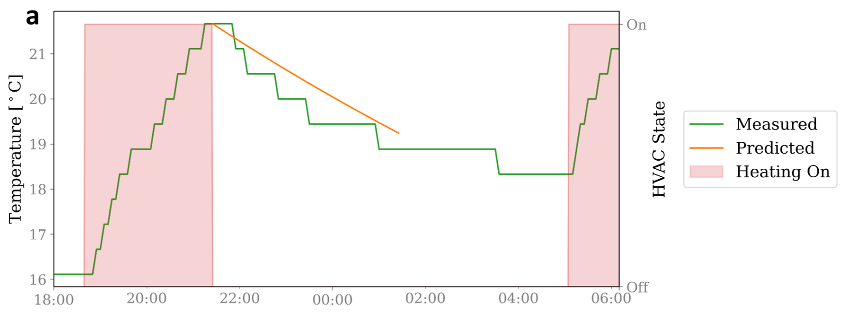
Temperature change — *Solar and internal heat gains*

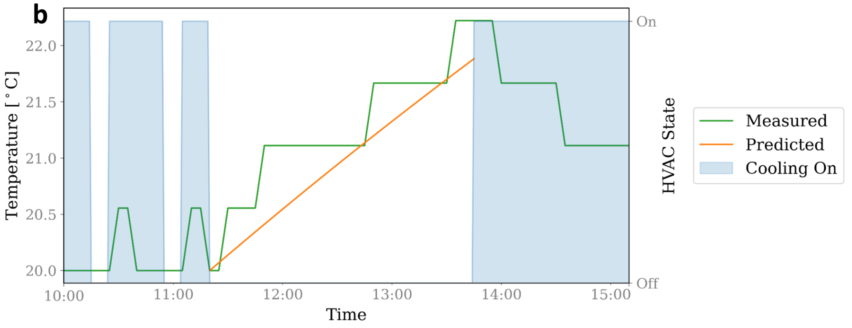
$$C\frac{dT_{in}}{dt} = \frac{(T_{out} - T_{in})}{R} + \frac{T_{eq}}{R} + Q_{HVAC}$$

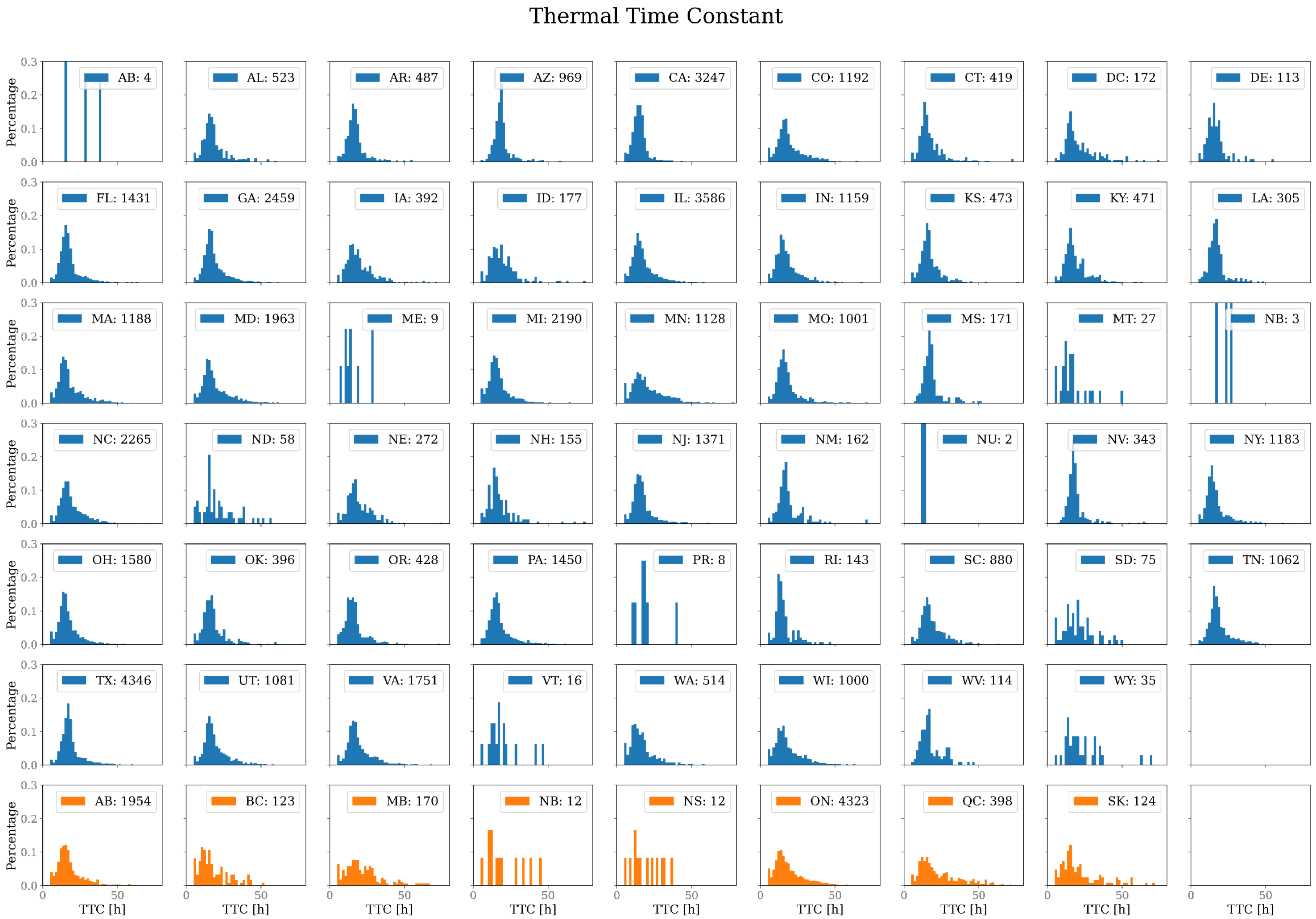
Heat transfer between indoor and outdoor — *Heat from HVAC*

Progress: FY21 - Infer building thermal properties

- Inferred thermal time constants for residential buildings in each state

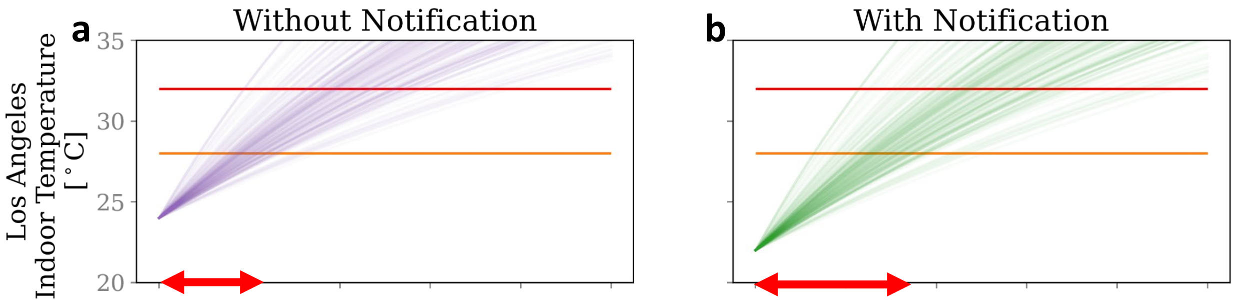






Progress: FY21 - Safe hours of no power during heatwaves

- **Rotating power outages may occur during heatwaves**
- **Plan power outage for resident's health and safety**
  - What is the ***maximum power outage duration*** that minimizes overheating risks of residents?
- **Simulate the house thermal dynamics using inferred properties**



Stakeholder Engagement

We've been engaging with ASHRAE 90.1, 189.1, and ASHRAE Building Energy Quotient (BEQ), and Alliance to Save Energy (ASE) about the system-level KPIs.

Annex 79

We are leading a book chapter on occupant KPIs under the IEA EBC Annex 79: occupant-centric building design and operation.

Annex 81

We are collaborating with IEA EBC Annex 81 on data-driven methods to quantify building energy flexibility.

- Engaged the EnergyPlus development team on implementing the inverse modeling feature
- Engaged the OpenStudio team on development of system and occupant KPIs reporting measures

Publications:

1. Z. Wang, T. Hong, H. Li. Informing the planning of rotating power outages on heat waves through data analytics of connected smart thermostats. Environmental Research Letters, 2021.
2. H. Li, Z. Wang, T. Hong. Energy flexibility characterization and quantification for residential buildings: A systematic review. Advances in Applied Energy, 2021.
3. H. Li, Z. Wang, T. Hong. Occupant-Centric Key Performance Indicators to Inform Building Design and Operations. Building Performance Simulation, 2021.
4. H. Li, T. Hong, S.H. Lee, M. Sofos. System-level Key Performance Indicators for Building Performance Evaluation, Energy and Buildings, 2020.
5. T. Hong, S.H. Lee. Integrating physics-based models with sensor data: An inverse modeling approach, Building and Environment, 2019.

Remaining Project Work (FY22)

Goal:

- Develop an ontology to represent flexibility resources and flexible loads in buildings
- Explore novel data-driven methods to quantify the flexibility potential of buildings
- Support GEB technologies modeling and evaluation through standardization and interoperability
- Continue engaging stakeholders

Main activities:

1. Conduct a systematic review on existing data ontologies and schemas ecosystem to identify gaps in representing building energy flexibility
2. Propose an ontology for energy flexibility to fill the gaps
3. Conduct a case study using the developed ontology and data-driven methods to quantify building energy flexibility
4. Publish results in a journal article

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $750k
Variances: N/A
Cost to Date: $410k
Additional Funding: N/A

Budget History					
FY 2020 (past)		FY 2021 (current)		FY 2022 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$220k	N/A	$280k	N/A	$250k	N/A

Project Plan and Schedule

Project Schedule												
Project Start: October 1, 2019	(Completed Work)	Completed Work										
Project End: September 30, 2022	(Active Task)	Active Task (in progress work)										
	◆ (red)	Milestone/Deliverable (Originally Planned)										
	◆ (black)	Milestone/Deliverable (Actual)										
	FY2020				FY2021				FY2022			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
FY20 Q3 Milestone: Occupant-centric KPIs review and synthesis	■	■	■ ◆									
FY21 Q1 Milestone: Occupant-centric KPI OpenStudio reporting measure				■	■ ◆							
FY21 Q2 Milestone: Inverse method to infer building thermodynamics with smart thermostat data					■							
FY21 Q2 Milestone: Power outage planning using the infered building thermodynamics						■ ◆						
FY21 Q3 Milestone: Review of residential building energy flexibility characterization and quantification						■	■ ◆					
Current/Future Work												
FY22 Q1 Milestone: Energy flexibility ontology								■	■ ◆ (red)			
FY22 Q4 Milestone: Data-driven moethod to quantify energy flexibility									■	■	■	■ ◆ (red)