U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

GEB Technical Report Series: Heating, Ventilation, and Air Conditioning

Building Technologies Office

June 2, 2020

Webinar Agenda

I. **GEB Overview**
   - Monica Neukomm, Senior Policy Advisor
     - Building Technologies Office

II. **GEB HVAC, Water Heating, Appliances, and Refrigeration Report**
   - Matt Guernsey, Associate Director
     - Guidehouse Consulting (Navigant)

III. **HVAC Flexibility Metrics**
   - Nelson James, Science, Technology, and Policy Fellow
     - Building Technologies Office

IV. **Quantifying Flexibility Potential**
   - Nelson James, Science, Technology, and Policy Fellow
     - Building Technologies Office

V. **Q&A Session**
   - Antonio Bouza, HVAC, Water Heating, and Appliances Technology Manager Technology Manager
     - Building Technologies Office



GEB Technical Report Webinar Series

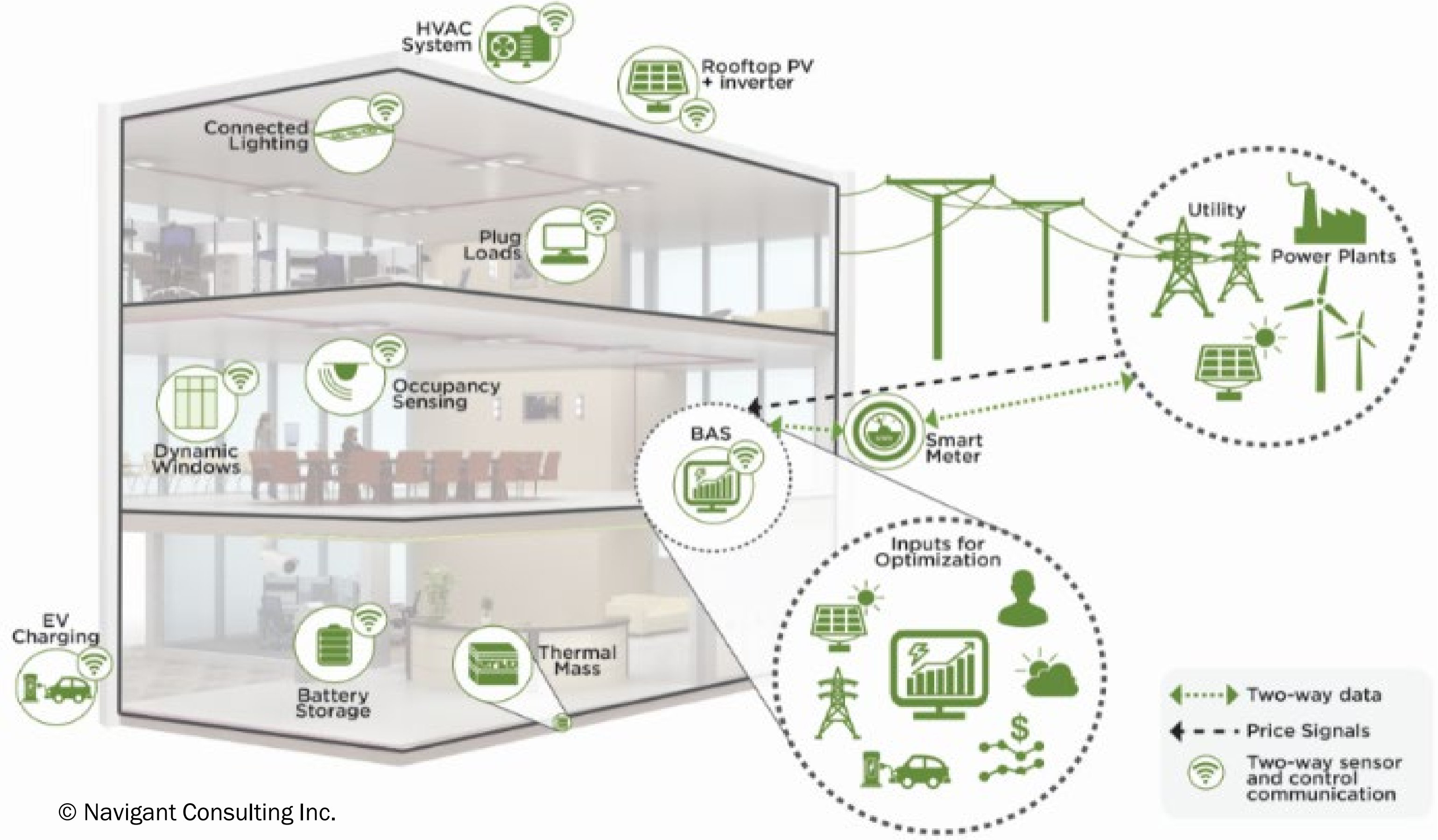
Topic	Date	Time
Whole-building Control, Sensing, Modeling & Analytics	May 19	2:00pm - 3:30pm ET
Lighting & Electronics	May 26	2:00pm - 3:00pm ET
Heating, Ventilation & Air Conditioning (HVAC)	June 2	2:00pm - 3:30pm ET
Water Heating & Appliances	June 9	2:00pm - 3:00pm ET
Envelope & Windows	June 16	2:00pm - 3:30pm ET
Integration - Building Equipment	June 23	2:00pm - 3:00pm ET
Integration –Distributed Energy Resources (DERs)	June 30	2:00pm - 3:00pm ET

GEB Technical Report Series Overview

The GEB Technical Report Series outlines key demand flexibility opportunities across BTO's R&D portfolio:
http://energy.gov/eere/buildings/grid-interactive-efficient-buildings

Technical Report Series:

- Overview of Research Challenges
- Heating, Ventilation, & Air Conditioning (HVAC); Water Heating; and Appliances
- Lighting & Electronics
- Building Envelope & Windows
- Sensors & Controls, Data Analytics, and Modeling



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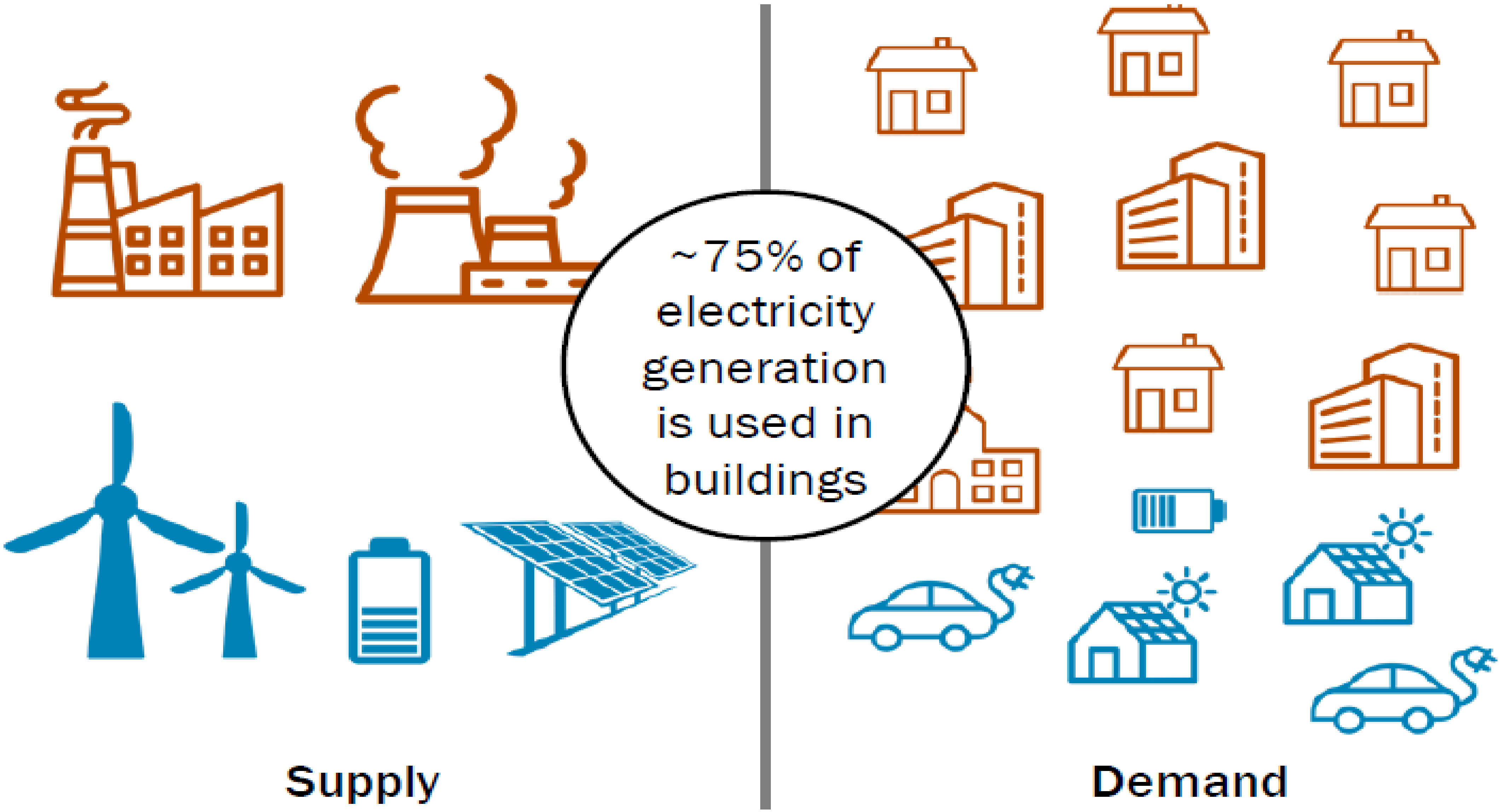
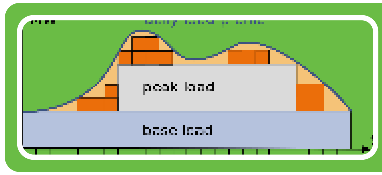
GEB is about enabling buildings to provide flexibility in energy use and grid operation



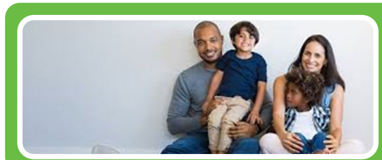
Potential Benefits of Flexible Building Loads

✓ Energy Affordability



✓ Improved reliability & resiliency

✓ Reduced grid congestion



✓ Enhanced services

✓ Environmental benefits

✓ Customer choice

Key Characteristics of GEBs

EFFICIENT

Persistent low energy use minimizes demand on grid resources and infrastructure

CONNECTED

Two-way communication with flexible technologies, the grid, and occupants

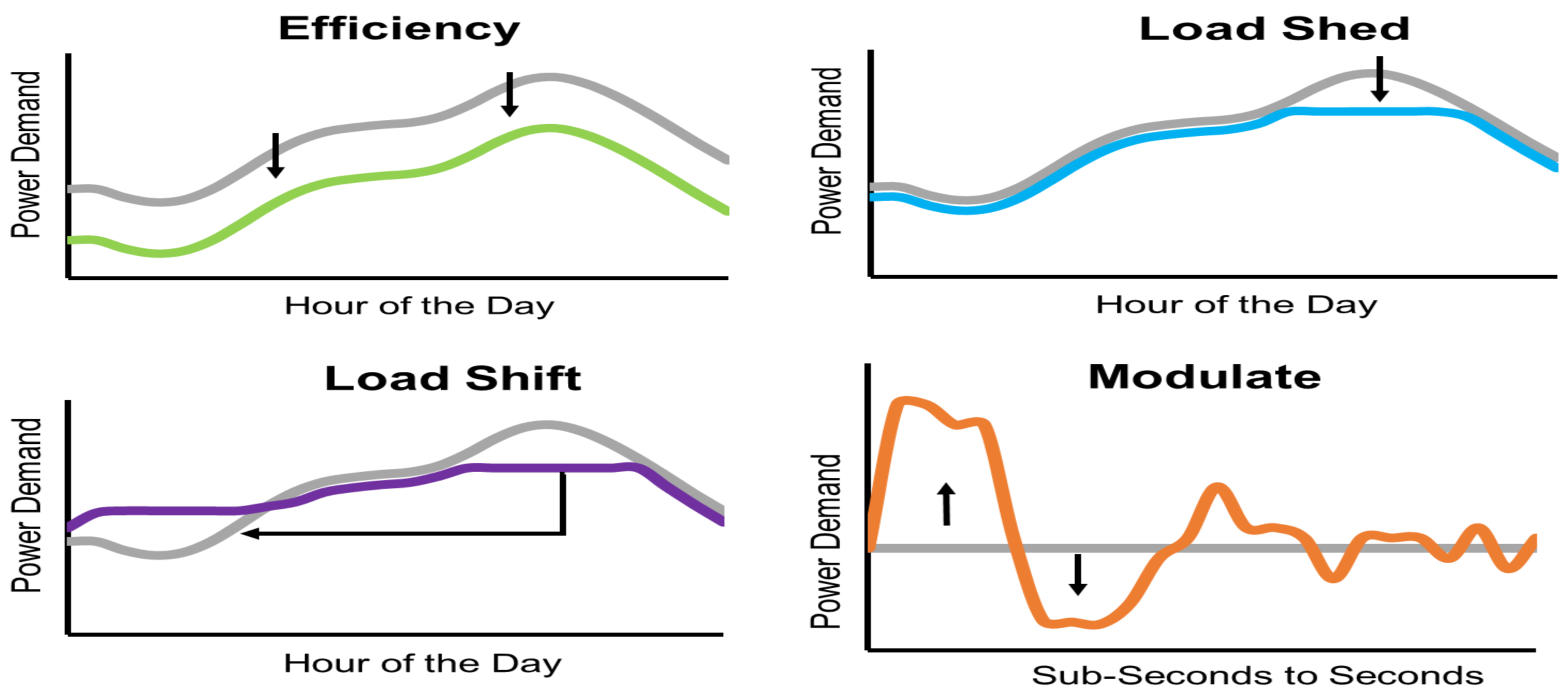
SMART

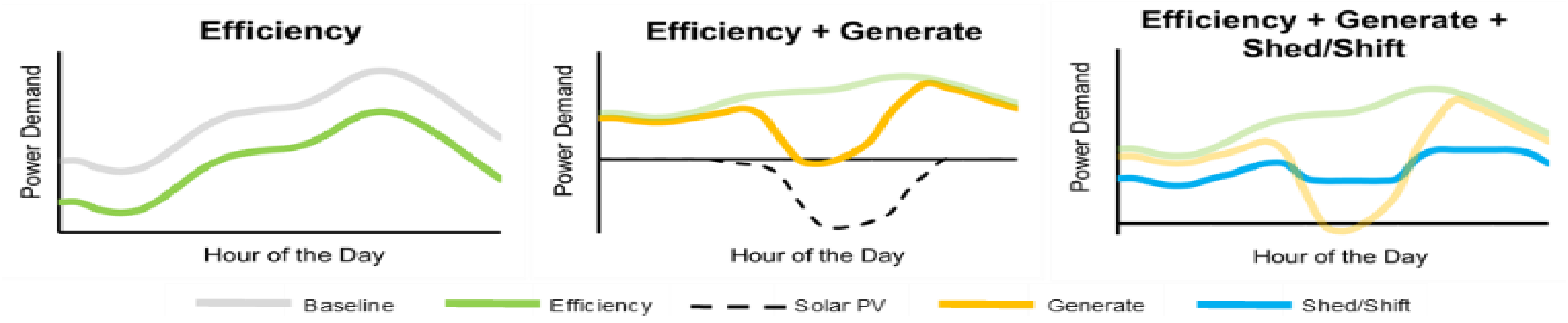
Analytics supported by sensors and controls co-optimize efficiency, flexibility, and occupant preferences

FLEXIBLE

Flexible loads and distributed generation/storage can be used to reduce, shift, or modulate energy use

Demand Management Provided by GEB

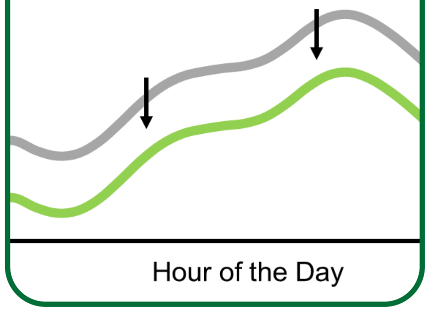




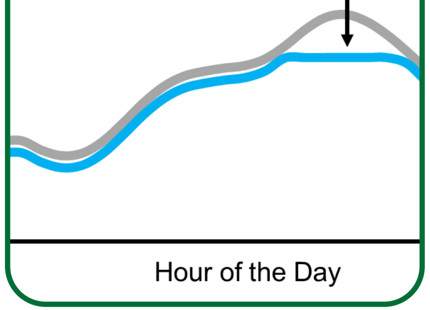
Mapping Flexibility Modes and Grid Services

Buildings can provide grid services through 4 demand management modes.

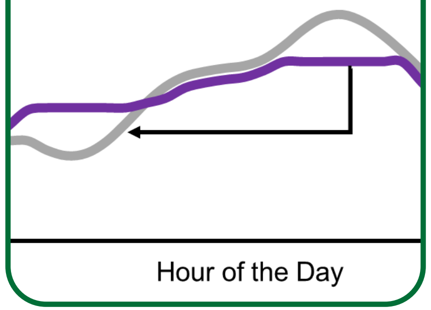
Efficiency



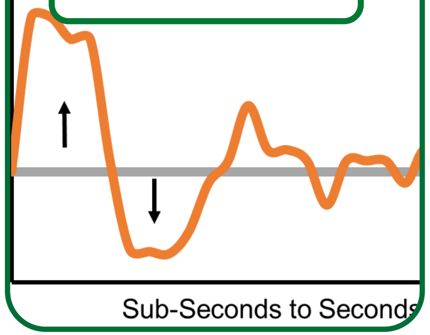
Load Shed



Load Shift



Modulate



Grid Services Provided

Efficiency	Load Shed	Load Shift	Modulate
• Generation: Energy & Capacity • Non-Wires Solutions	• Contingency Reserves • Generation: Energy & Capacity • Non-Wires Solutions	• Generation: Capacity • Non-Wires Solutions	• Frequency Regulation • Ramping

Examples

Efficiency	Load Shed	Load Shift	Modulate
• Daylighting with sensors & controls	• Reduce plug loads	• Precool with T-stat; preheat water heater	• Rapid dimming of lighting

GEB HVAC, Water Heating, Appliances and Refrigeration Report

Matt Guernsey
Guidehouse

Lead Authors

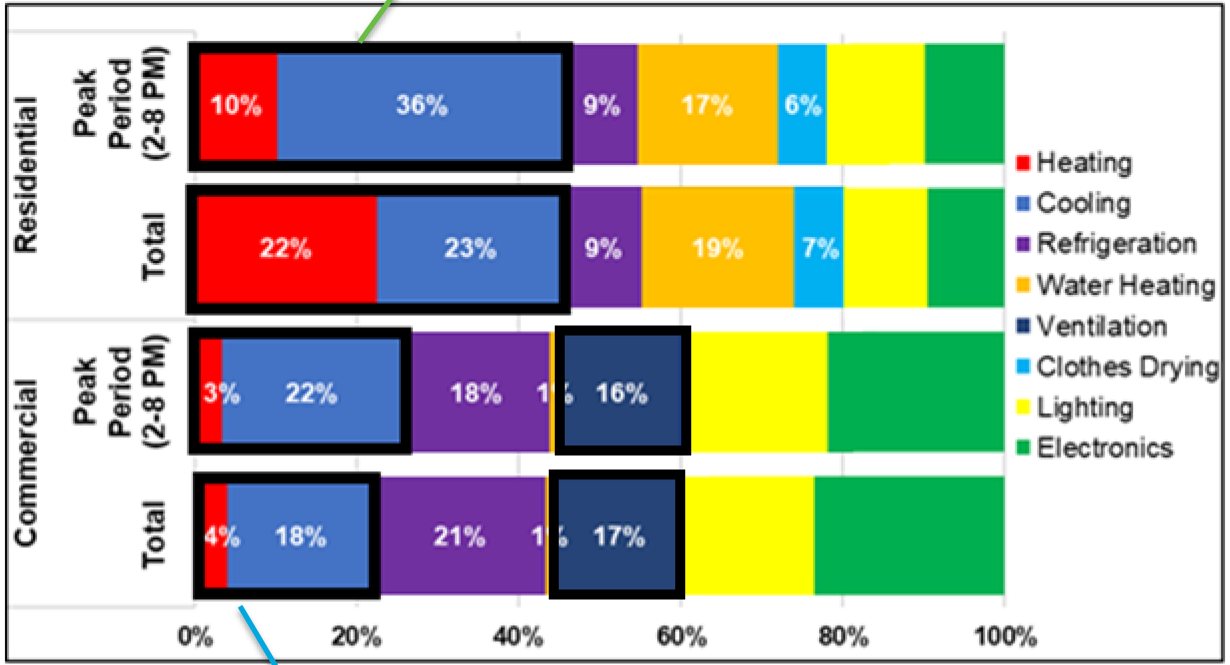
Bill Goetzler, Navigant Consulting, Inc.
Matt Guernsey, Guidehouse
Theo Kassuga, Guidehouse

Significant Contributions

Jim Young, Guidehouse
Tim Savidge, Guidehouse

Importance of HVAC for GEB

U.S. 2018 Annual Electricity Use



HVAC electricity use in homes:

- 46% of peak
- 45% of total

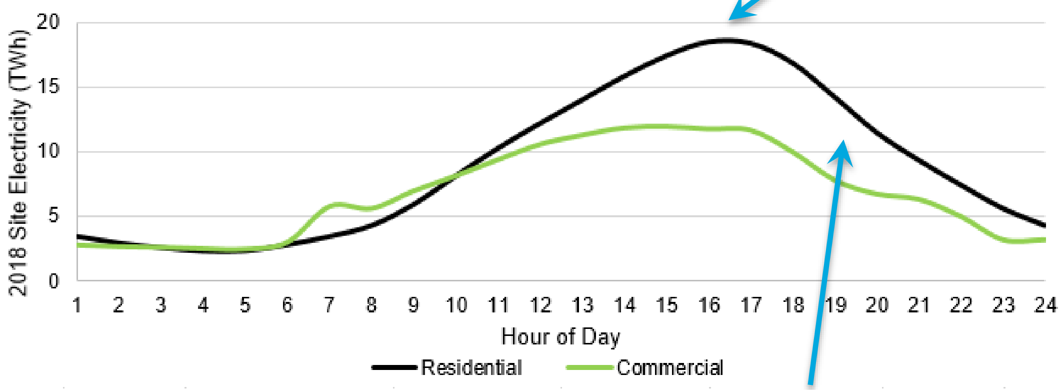
HVAC electricity use in commercial buildings:

- 41% of peak
- 39% of total

Value of flexible HVAC

Electric Space Cooling

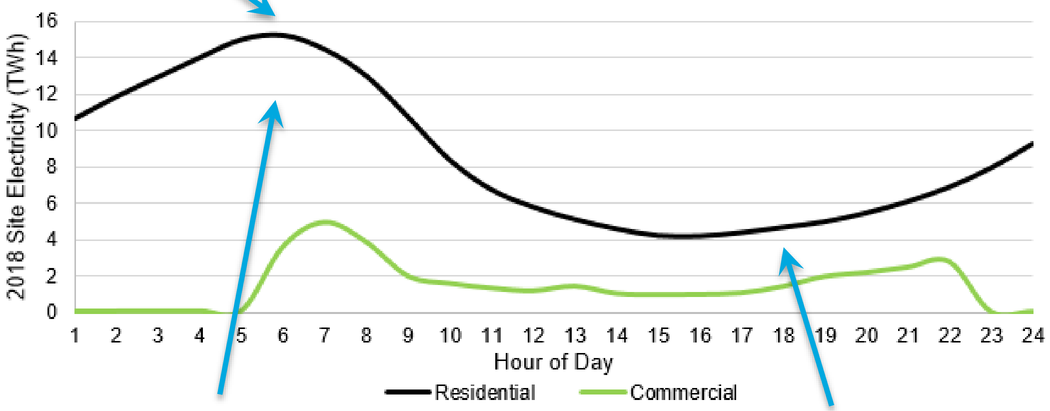
Substantial peak relative to trough, highlighting load shifting opportunity



Notable elevated load after sundown

- A/C load growth continues in most regions
- Utility concern: continued peak load growth on hottest days summer

Electric Space Heating



Early morning peak before sunrise

Substantially non-coincident with solar availability

- Common in the southeast; elsewhere gaining momentum via electrification trend
- Utility concern: switch to winter peak

From the Controls, Sensing & Modeling Report …

- **Greatest GEB opportunity is to use building thermal mass to proactively shift HVAC loads "ahead" in time. If done properly:**
  – Minimize occupant impacts
  – Minimize "recovery" effects

- **Assertion: shifting of HVAC loads should be provisioned at the highest level of coupling between thermal storage and HVAC system**
  – Device level for residential AC
  – District level for district hot/chilled water systems
  – Building or zone level depending on configuration

Report Objectives

- What HVAC technologies can provide grid services?
- Which have the highest potential?
- What R&D is needed to overcome current challenges inhibiting their performance and/or adoption?

Process

Technology Evaluation

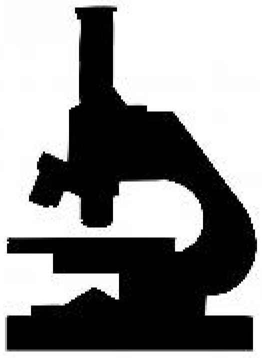
- Potential for shed, shift, and modulate

Technology Attributes

- Strengths, weaknesses, hurdles to market success

R&D Opportunities

- Needs and initiatives where DOE can add value



Technology Flexibility Analysis Results

	HVAC	Cross Cutting
High Potential	• HVAC#1: Smart Thermostats • HVAC#2: Separate Sensible/Latent Space Conditioning • HVAC#3: Liquid Desiccant TES	• CC#1: Thermal Energy Storage • CC#3: Non-Vapor Compression (NVC) Materials and Systems
Medium Potential	• HVAC#4: Advanced Controls for HVAC Equipment with Embedded Thermostats	• CC#2: Modulating Capacity Vapor Compression
Low Potential	• HVAC#5: Hybrid Evaporative Cooling • HVAC#6: Dual-Fuel HVAC	• None

Evaluation of Technologies

We used 3 basic criteria to evaluate the technologies.

1. **Capability Rating for demand side management (DSM) strategy**
   – Based on Grid Services Technical Requirements

Capability Ratings							
	Not Applicable		Low Capability		Medium Capability		High Capability

2. **Number of demand-management strategies provided**
   – I.e., Efficiency, Load Shed, Load Shift, Modulate
3. **Weighting of demand-management strategies**
   – Efficiency and peak reductions (shed/shift) higher value than frequency regulation, voltage support, ramping (modulate)

Technology Evaluation Details

Capability Legend: NA Low Med High

	Technologies	Efficiency	Load Shed	Load Shift	Modulate	Overall Potential
HVAC	HVAC#1: Smart Thermostats	Low	Med	High	Low	High
	HVAC#2: Separate Sensible and Latent Space Conditioning	High	Med	Med	NA	High
	HVAC#3: Liquid Desiccant Thermal Energy Storage	Med	Med	High	NA	High
	HVAC#4: Controls for HVAC Equipment w/Embedded T-stats	NA	Low	High	Low	Med
	HVAC#5: Hybrid Evaporative Precooling	High	Low	Low	NA	Low
	HVAC#6: Dual-Fuel HVAC	NA	High	NA	NA	Low
Cross Cutting	CC#1. Thermal Energy Storage (TES)	Low	Low	High	Low	High
	CC#2. Modulating Capacity Vapor Compression	High	Med	Med	Med	Med
	CC#3. Non-Vapor Compression (NVC) Systems and Materials	High	Med	High	Med	High

HVAC Technologies Evaluated

#1: Smart Thermostats

Flexibility Mode	Capability
Efficiency	◑
Shed Load	◐
Shift Load	●
Modulate Load	◑

Technology

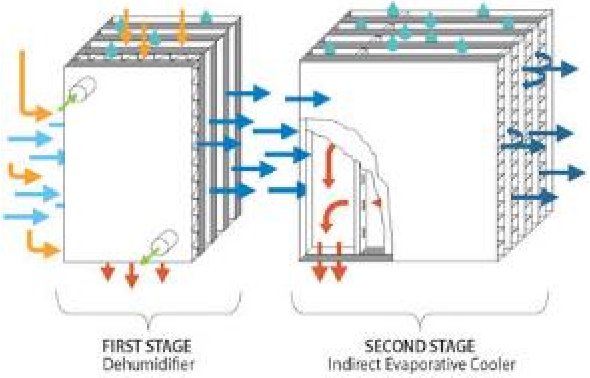
- Thermostats with connectivity, advanced algorithm controls, and compatibility with home automation systems

Flexibility

- Adding advanced controls and remote operation for relatively simple HVAC systems

https://www.ecobee.com/en-us/smart-thermostats/

#2: Separate Sensible and Latent Space Conditioning



Flexibility Mode	Capability
Efficiency	●
Shed Load	◐
Shift Load	◐
Modulate Load	○

Technology

- Desiccants, membranes for dedicated dehumidification; paired with a sensible cooling stage with separate controls

Flexibility

- Ramping down only the sensible cooling provides load reduction – maintains substantive occupant comfort

https://www.nrel.gov/docs/fy13osti/57624.pdf

HVAC Technologies Evaluated Cont.

#3: Liquid Desiccant Thermal Energy Storage

Flexibility Mode	Capability
Efficiency	◐
Shed Load	◐
Shift Load	●
Modulate Load	○

Technology:

- Liquid desiccant storage for dehumidification in SSLSC; regenerated desiccants store energy chemically at ambient temp

Flexibility:

- Allows for shifting of dehumidification load to off-peak hours.

https://www.rheem.com/

#4: Advanced Controls for HVAC w/Embedded T-stats

Flexibility Mode	Capability
Efficiency	○
Shed Load	◑
Shift Load	●
Modulate Load	◑

Technology:

- Many small A/C do not connect to smart thermostats
- They require their own advanced communications and connected controls

Flexibility:

- Wi-fi connectivity and mobile-app-based controls allow HVAC-ETs to communicate with utilities for curtailment

https://www.lg.com/

HVAC Technologies Evaluated Cont.

#5: Hybrid Evaporative Precooling

Flexibility Mode	Capability
Efficiency	●
Shed Load	◐
Shift Load	◐
Modulate Load	○

Technology

- Evaporative cooling can be combined with other primary cooling stages to increase efficiency, especially in low humidity regions.

Flexibility

- Controls can optimize use of one or both cooling stages

https://peakplus.energy/

#6: Dual-Fuel HVAC

Flexibility Mode	Capability
Efficiency	○
Shed Load	●
Shift Load	○
Modulate Load	○

Technology

Example configurations could include:

- [Heating] Fuel-fired furnace + electric heat pump (residential split or commercial RTU)
- [Heating] Gas/propane/oil boiler + ductless heat pumps

Flexibility

- Provide load shedding by temporarily switching fuels

https://www.fujitsugeneral.com/
https://www.weil-mclain.com/

Cross Cutting Technologies Evaluated

CC#1. Thermal Energy Storage (TES)

Flexibility Mode	Capability
Efficiency	◑
Shed Load	◑
Shift Load	●
Modulate Load	◑

Technology

- TES may be stand-alone or be embedded within other equipment. Examples:
  - Heating or Cooling: Water/Ice or phase change materials (PCMs) stored in tanks
  - Gas absorption: Separate storage of the sorbent and refrigerant mid cycle for long-term, no-loss, storage

Flexibility

- Off-peak recharging enables load shifting

https://www.bradfordwhite.com/

CC#2. Modulating Capacity Vapor Compression

Flexibility Mode	Capability
Efficiency	●
Shed Load	◐
Shift Load	◐
Modulate Load	◐

Technology

- Modulating allows for more granular control than provided by single-speed systems.

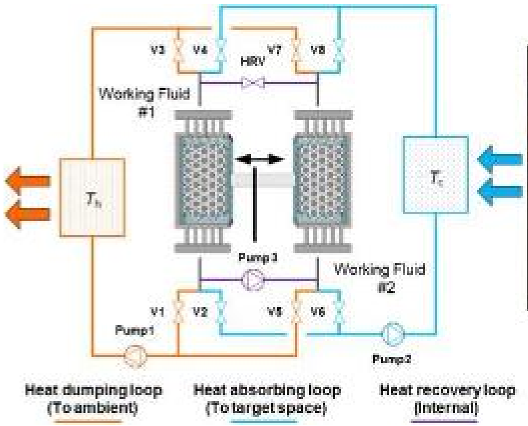
Flexibility

- Modulation increases precision of load control for load shifting and improves efficiency.

https://climate.emerson.com/en-us

Cross Cutting Technologies Evaluated Cont.

CC#3. Non-Vapor Compression (NVC) Systems and Materials



Flexibility Mode	Capability
Efficiency	●
Shed Load	◐
Shift Load	●
Modulate Load	◐

Technology

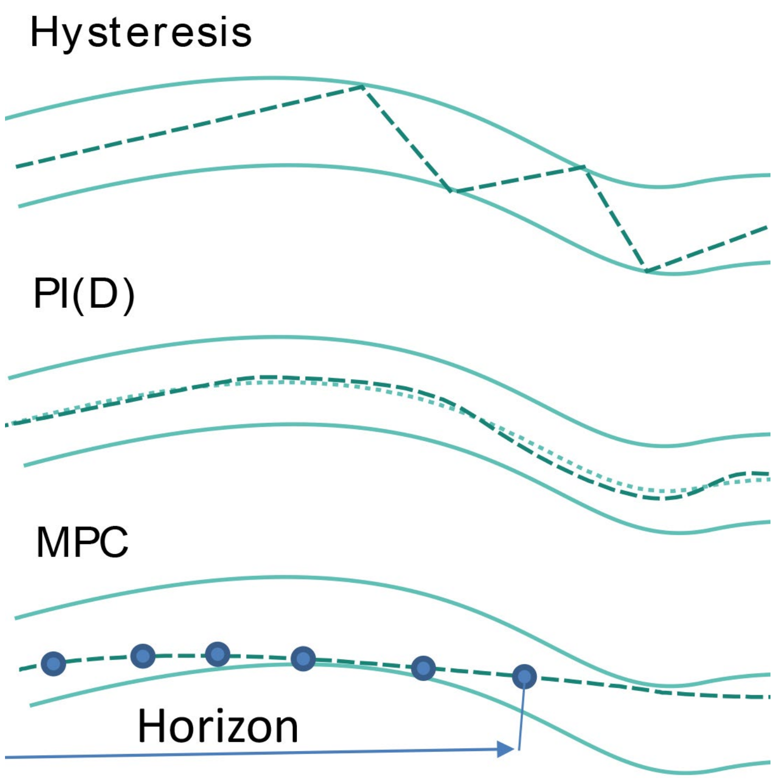
- Multiple types: may use unique properties of materials or new architectures.
- Examples:
  - Solid-state NVC: thermoelectric, magnetocaloric, electrocaloric
  - Other NVC: Membrane, thermoelastic, Stirling, liquid desiccant, thermoacoustic

Flexibility

- Modulating capacity, separate sensible/latent controls, and energy storage

Controls Report Technology: Model Predictive Control

- **HVAC demand is weather dependent, proactive load shifting relies on predictions of weather, occupancy, and grid needs**
- **Model predictive control (MPC)**
  - Broad sense of the term: optimization over receding time horizon using predictions and updates
  - Already in use: district systems, some large buildings
  - Can optimize for multiple objectives
  - Can create for counterfactuals for bidding and M&V
  - Incorporate weather dependent generation, storage?



Poll

Based on potential grid flexibility impact and likelihood of adoption, of the evaluated technologies, select the two that you think DOE should prioritize :

- Smart Thermostats
- Separate Sensible and Latent Space Conditioning
- Thermal Energy Storage
- Liquid Desiccant Thermal Energy Storage
- Advanced Controls for HVAC Equipment with Embedded Thermostats
- Hybrid Evaporative Precooling
- Dual Fuel HVAC
- Modulating-Capacity Vapor Compression
- Non-Vapor-Compression (NVC) Materials/Systems

Challenges & Opportunities: All Connected Technologies

	Challenge	Opportunity
All Connected Technologies	Interoperability	Standardized semantic and syntactic specifications for connected devices and software systems
	Cybersecurity	Secure system architectures and cybersecurity best practices
	Cost	New manufacturing processes with low capital cost or use of existing manufacturing equipment
		New materials and technologies compatible with scalable manufacturing methods

Challenges & Opportunities: HVAC Technologies

	Challenge	Opportunity
All HVAC GEB Technologies	Limited understanding of duration/temp/humidity curtailment constraints	Modelling/testing (including behaviour) to characterize curtailment limits
Separate Sensible and Latent Space Conditioning	Installation & commissioning complexity	Packaged systems to reduce installation/commissioning complexity
Liquid Desiccant TES	Installation & commissioning complexity	Packaged systems to reduce installation/commissioning complexity
	Large footprint	Novel materials with greater energy storage density and/or novel packaging
Controls for HVAC w/ Embedded Thermostats	Lack of non-premium connected products	Inexpensive retrofit grid-interactive packages

Challenges & Opportunities: Cross Cutting Technologies

	Challenge	Opportunity
Thermal Energy Storage	Installation & commissioning complexity	Packaged systems with reduced installation/commissioning complexity
	Large footprint	Materials with increased energy storage density and/or novel packaging
	Limited year-round use	Dynamic manipulation of material transition temp and optimize operations
Modulating-Capacity Vapor Compression	High product costs	Lower-cost systems, focusing on heat exchangers & compressors
Non-Vapor-Compression (NVC) Materials/Systems	High product costs	Lower-cost NVC materials, systems, and components
	Limited field validation of architectures & approaches	Development of NVC for a broad range of applications

Controls Report: Challenges and Needs

- **Occupant interaction**
  - Accurate, cost-effective, privacy-preserving methods of measuring comfort
  - Feedback mechanisms to register preferences, change uncomfortable conditions
- **MPC**
  - Model acquisition, training and calibration
  - Interpretability and acceptance by occupants and operators
  - Adaptation to changing conditions
  - Uncertainty management

Poll

Identify the 2 highest priority areas to improve the flexibility potential provided by HVAC?

- Advanced controls, connectivity, and communications
- Interoperability and cybersecurity
- Occupant behavior and ensuring comfort/productivity
- Improved individual end-use equipment flexibility
- Development of flexibility-specific equipment (e.g., thermal energy storage)

Technical Report Q&A?

Use the question feature to ask a question or provide a comment.

Flexibility Metrics for Heating, Ventilation, and Air Conditioning Equipment

Nelson James
Building Technologies Office







Equipment Performance Metrics

- **A variety of metrics have been traditionally used to quantify the performance of HVAC equipment. These can allow for the direct comparison of systems with one another.**

Metric	Description
COP, EER	Coefficient of performance and energy efficiency ratio: Thermal power delivered divided by the electrical power input at a specified operating condition
SEER	Seasonal energy efficiency ratio: Cooling output during a typical cooling-season divided by the total electric energy input during the same period
IEER	Integrated Energy Efficiency Ratio: a measure that expresses cooling part-load EER efficiency for commercial unitary air-conditioning and heat pump equipment on the basis of weighted operation at various load capacities.
HSPF	Heating seasonal performance factor: ratio of heat output over a heating season to the electricity consumed.
AFUE	Annual fuel utilization efficiency: ratio of the annual heat output over the annual fuel energy consumed
Capacity	The quantity of heat that a system can add or remove from an enclosed space during a specified amount of time.

Potential Equipment Flexibility Metrics

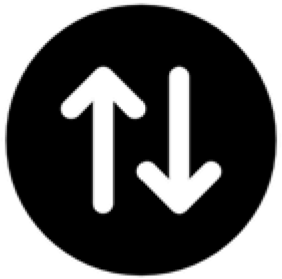
- **HVAC's ability to provide flexibility depends on equipment capabilities and associated characteristics of respective storage media (eg. Building mass/state of charge, occupancy/usage)**
- **In a similar manner to efficiency, metrics are needed to compare the ability of systems to provide flexibility.**

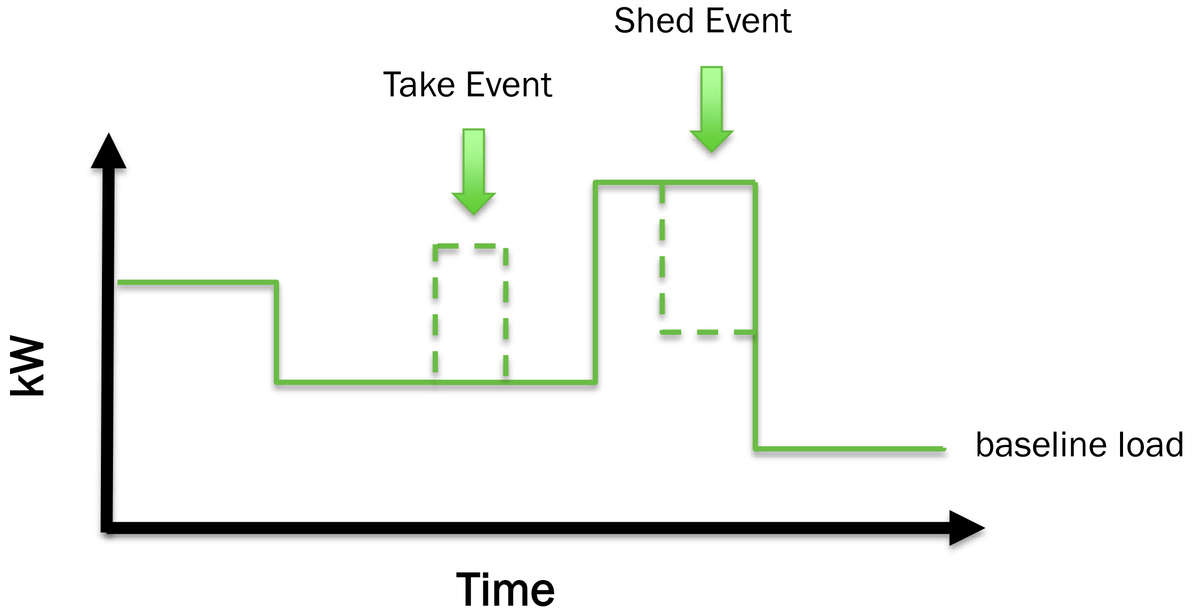
- Load Change During Event
- Duration of Response
- Resolution of Control
- Response Time

- Load Shift Capacity
- Load Shift Efficiency
- Lifetime Impacts
- Reliability of Response

Load Change During Event

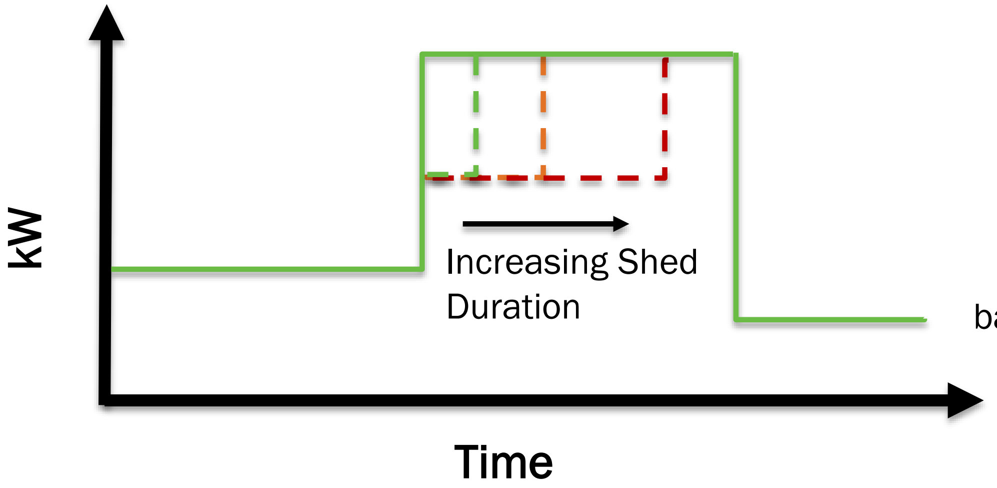
- **Equipment can be required to increase load when for example renewable energy is abundant and reduce load when the grid is constrained**
- **Quantification of how much the load can change in response to a signal.**
  – Percentage change of rated load [%]
  – Load increase or decrease [kW]





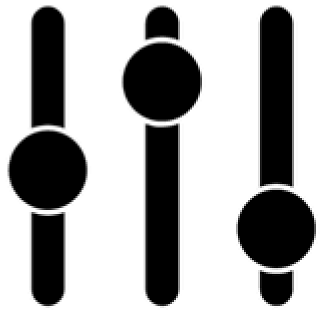
Duration of Response

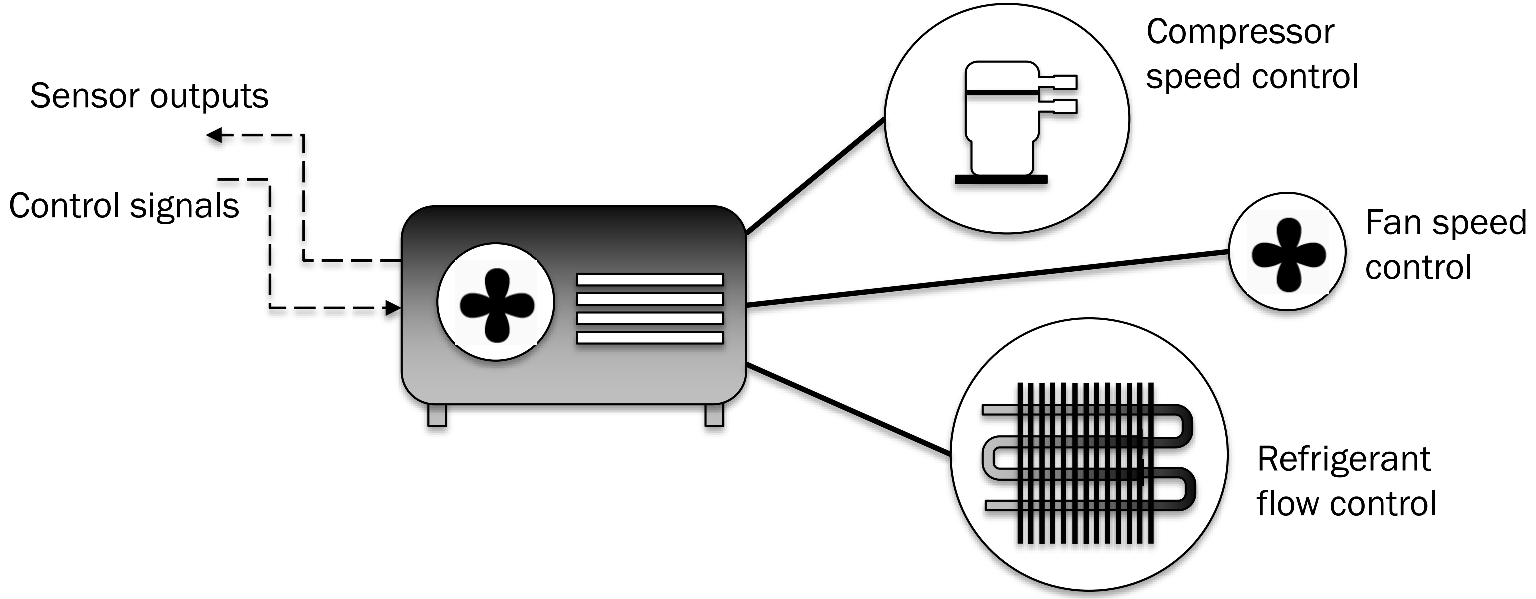
- The length of time that flexibility services can be provided without leading to unacceptable conditions for the occupants
- Generally depends on characteristics beyond the equipment’s capabilities such as the building thermal inertia and occupant behavior
  - Duration [hrs]



Resolution of Control

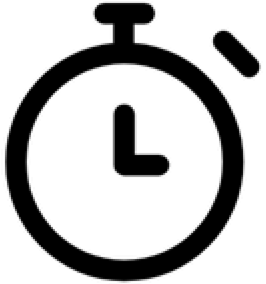
- **Control interfaces are needed for communication with automation systems and grid signals**
- **Additionally being able to operate at multiple power draws could increase options for flexibility**
  - Number of modes of control [-]

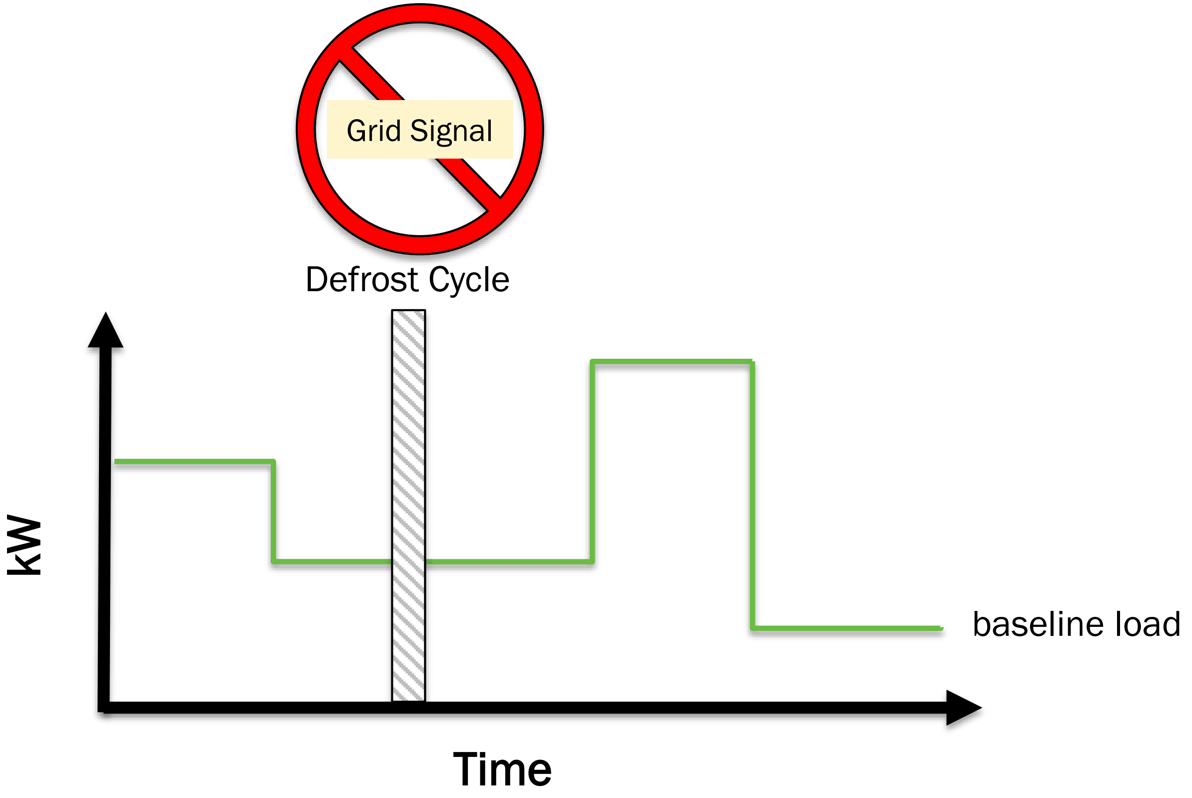




Response Time

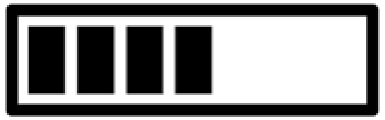
- **How quickly the equipment's operation change once a control signal is received**
- **Equipment processes could delay responses to flexibility services**
  - Defrost cycles [mins]
  - Compressor shutoff [hrs]



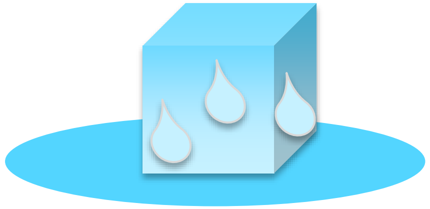


Load Shift Capability

- Measure of how much energy can be stored for shifting energy usage from the grid
- Dependent on thermal mass of building or active storage system
- Includes not only quantity of energy, but how quickly that energy can be utilized
  - Load Shift Capacity [kWh]
  - Load Shift Power [kW]



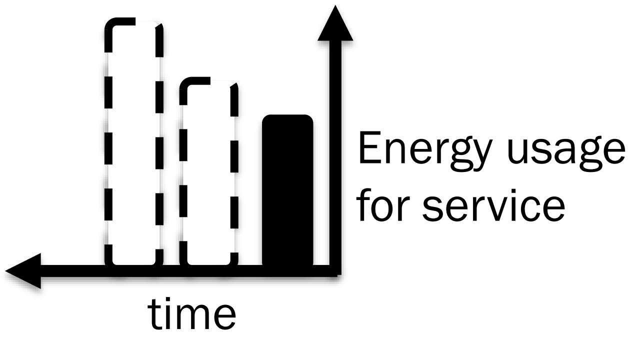
Thermal Mass

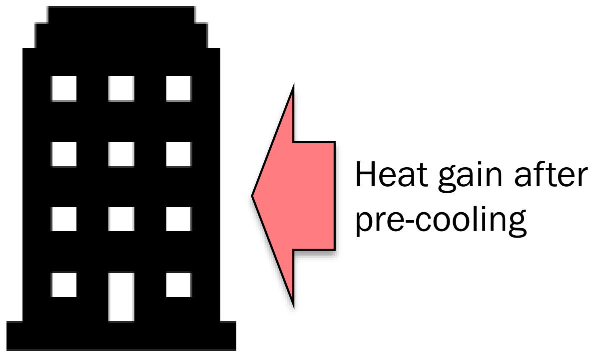


Ice Storage

Load Shift Efficiency

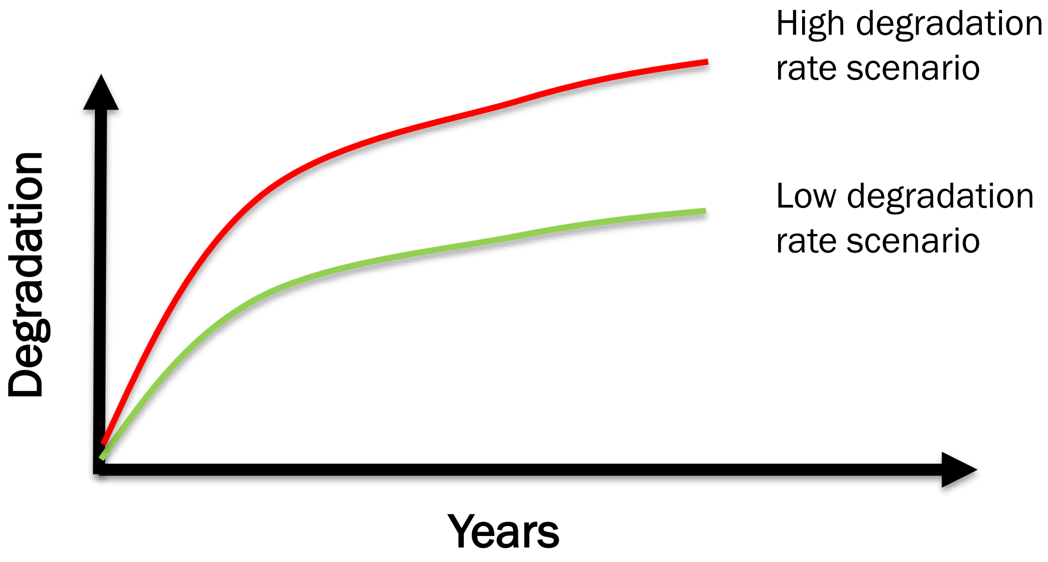
- **If energy is stored for shifting, inefficiencies of the storage and extraction process can lead to increase energy consumption**
- **Potential losses include heat gain or loss from the storage medium and thermal resistances between the storage medium and the HVAC equipment**
  - Storage efficiency [%]
  - Energy usage increase [kWh]





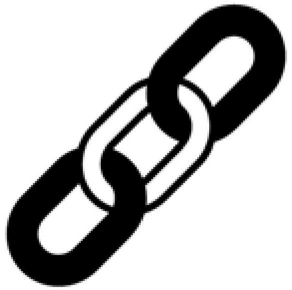
Lifetime Impacts

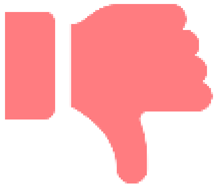
- **Extent to which providing services could impact equipment life from cycling, or running in non-standard operation**
  - Maintenance cost [$]
  - Maintenance intervals [hrs]
  - System life [yrs]



Reliability of Response

- **Depending on the severity of the impact on occupant services from a flexibility measure, the rate at which customers opt out of programs could vary**
- **Building characteristics and occupant behavior can influence the reliability at which a desired flexibility response is provided**
  – Percentage of Opt-Outs [%]





Poll

- **Eight metrics were presented:**

1. Load change during event
2. Duration of Response
3. Resolution of Control
4. Response Time
5. Load Shift Capacity
6. Load Shift Efficiency
7. Lifetime Impacts
8. Reliability of Response

Do you have recommendations for additional metrics, or changes to the current metrics?

Enter feedback into the Q&A box

Metrics Q&A?

Use the question feature to ask a question or provide a comment.

Quantifying Flexibility Opportunity of HVAC Equipment

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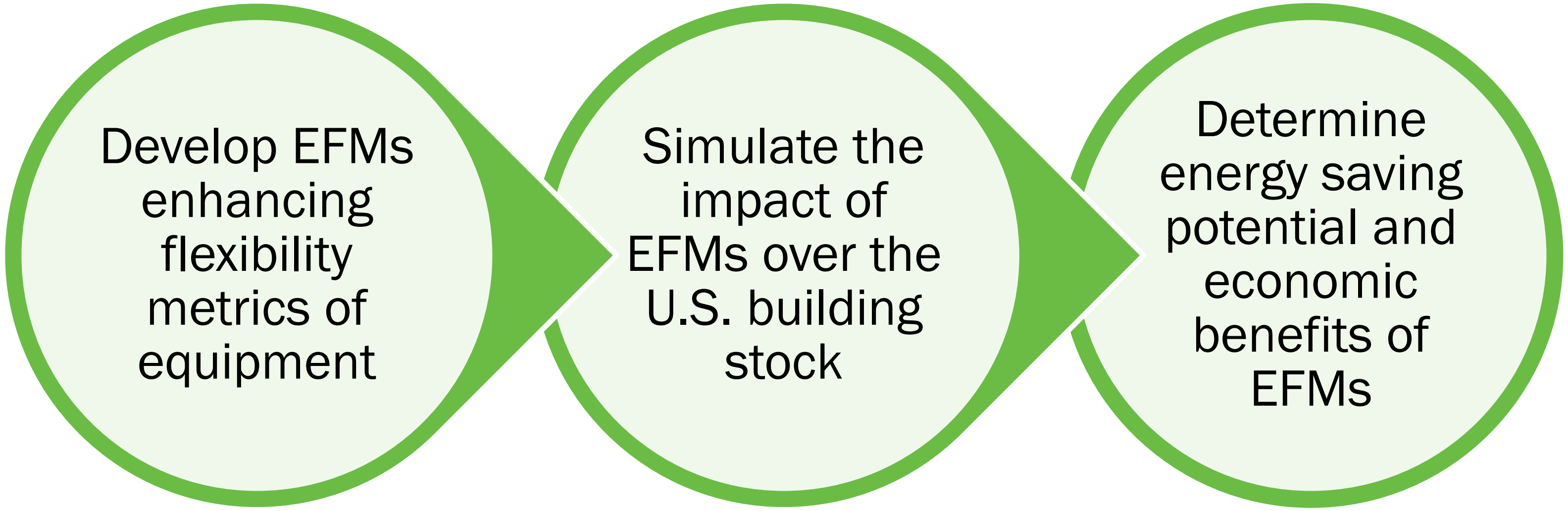
Quantifying Flexibility Opportunity

- **A consistent framework is needed to assess the impact of energy flexibility measures (EFMs) on the ability of residential and commercial buildings to provide load flexibility**
- **Using this framework, energy savings and cost targets can be associated with respective flexibility enhancements**



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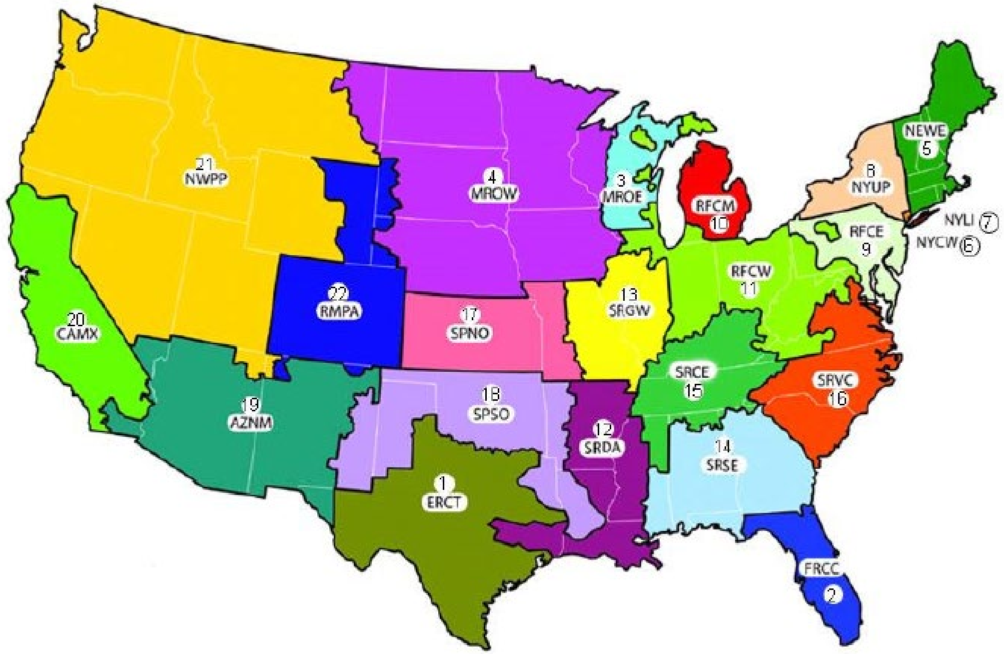
DOE Tools and Resources

eia	EIA provides a wide range of information and data products covering energy production, stocks, demand, imports, exports, and prices. The Electricity Market Module represents the capacity planning, generation, transmission, and pricing of electricity, subject to various factors including electricity load shapes and demand.
ResStock	A high level of granularity used to represent the diversity of housing stock characteristics and climates across the contiguous United States. The ResStock framework brings together the use of large public and private data sets, statistical sampling, detailed sub-hourly building energy simulations, and high-performance computing resources.
OpenStudio	OpenStudio® is a cross-platform collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. OpenStudio is an open source (LGPL) project to facilitate community development, extension, and private sector adoption.
scout U.S. DEPARTMENT OF ENERGY	Scout is a tool for estimating the energy and carbon impacts of various energy conservation measures (ECMs) on the U.S. residential and commercial building sectors

Proposed Analysis Process

- **Establish baseline grid load shapes**
  – For each of 22 EIA Electric Market Module (EMM) regions, determine how electricity demand varies over the year



U.S. EIA EMM regions

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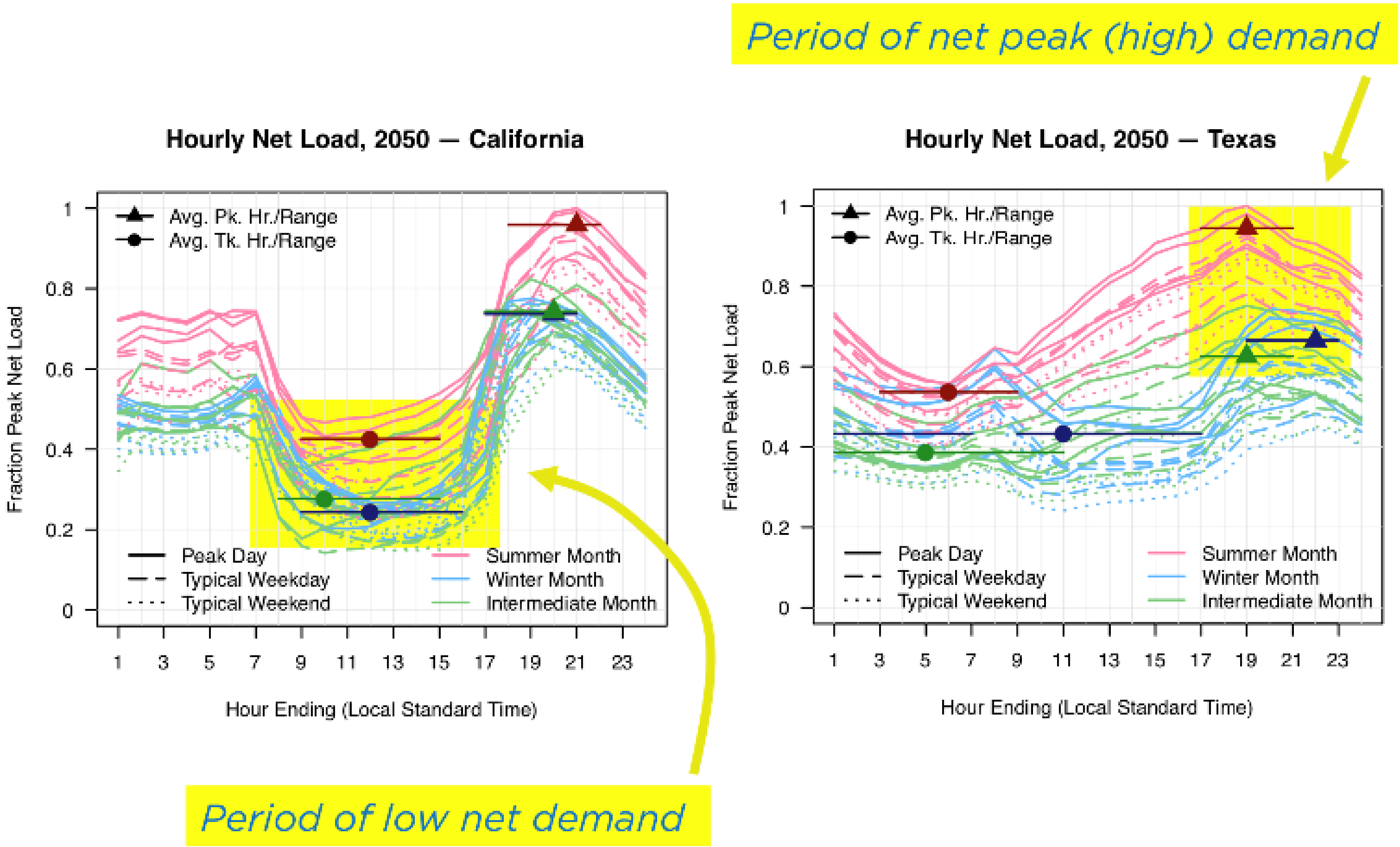
Proposed Analysis Process

- **Define windows for peak demand and low demand periods**
  - Based on seasonal load shapes, define windows of time where it could be beneficial to increase or decrease load
  - Peak demand windows currently set at 4 hours
  - Low demand windows based on when load is below a threshold percentage of the peak



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Proposed Analysis Process

- **Specify flexibility measures**
  - How equipment will response to provide flexibility during the peak demand and low demand periods

Measure	Description
Global temperature adjustment	Adjusts zone cooling temperature setpoint upwards and zone heating temperature setpoint downwards during the peak hours
Pre-conditioning	Pre-cool/pre-heat starting 4 hours before the peak, then set-back/set-up setpoint relative to original setpoint during peak period.
Ice storage	Charge ice storage between off peak hours. Discharge ice storage during the peak period.

⋮

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Proposed Analysis Process

- **Simulate measures across climate zones**
  - Using ResStock and commercial prototype building models, determine 8760 end-use building loads
  - Implement the flexibility measures in EnergyPlus to determine demand impacts while maintaining comfort constraints
  - Utilize peak demand and low demand definitions for respective EMM region
  - Determine EFM savings fraction relative to baseline

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Proposed Analysis Process

- **National assessment using scout**

  – Use Scout to assess the regional and national impacts of EFMs across future years
    - Energy savings
    - CO_2 savings
    - Cost Savings
    - EFM price premiums

scout
U.S. DEPARTMENT OF ENERGY

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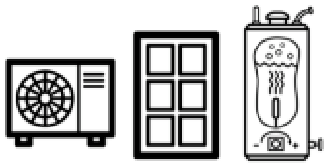
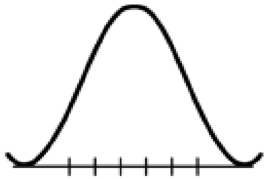
Proposed Analysis Process

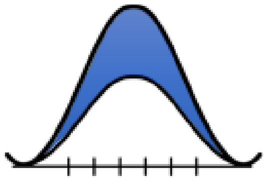
1. Define energy efficiency (EE), demand flexibility (DF), and EE + DF measure portfolios



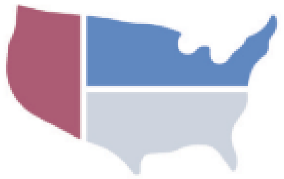
2. Develop 8760 hourly fractions of annual baseline load by climate, building type, and end use

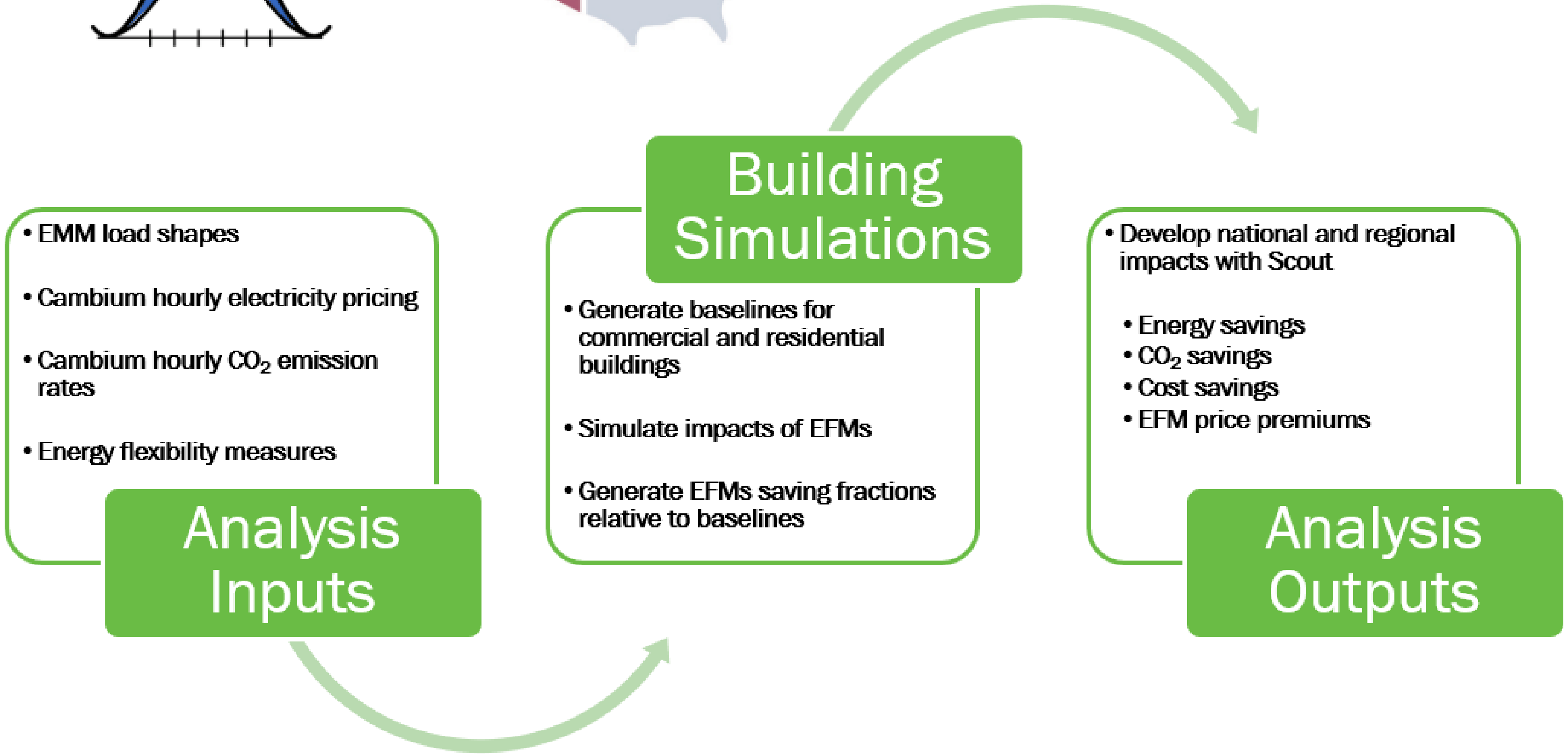


3. Develop bottom-up EnergyPlus measure simulations and 8760 savings fractions based on regional system needs



4. Translate measures to Scout and assess regional/national portfolio potential, annually and sub-annually (2015-2050)





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Poll

Does the analysis framework presented create a reasonable path to quantifying and comparing the capabilities of HVAC flexibility measures?

- Yes, the approach should be adequate to quantify the flexibility potential of HVAC equipment
- Almost, additional inputs are required in the analysis
- Almost, improvements are needed in EFM simulation approach
- Almost, relevant outputs are missing from the analysis
- No, analysis framework needs to be significantly altered

Open Q&A?

Use the question feature to ask a question or provide a comment.

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