U.S. DEPARTMENT OF ENERGY

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GEB Technical Report: Modeling, Sensing, Control, and Analytics

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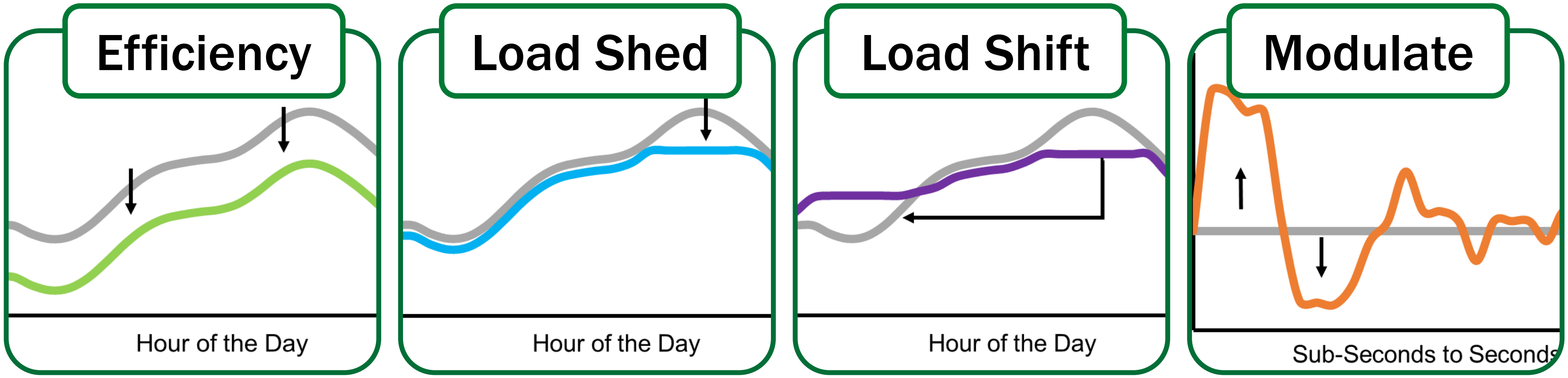
Session Outline

Topic	Time
Report Background	2:30 – 3:00
Discussion 1: M&V (Section 6)	3:00 – 3:30
Break	3:30 – 4:00
Discussion 2: MPC (Section 4)	4:00 – 4:30
Discussion 3: Characterization (Section 5)	4:30 – 5:00
Final Discussion: Cross-cutting issues	5:00 – 5:30

Demand Flexibility (DF) Modes & Grid Services

Main Flexibility Modes. (Plus Generation)



Grid Services Provided

Efficiency
- Generation: Energy & Capacity
- T&D: Non-Wires Solutions

Load Shed
- Con. Reserves
- Generation: Energy & Capacity
- T&D: Non-Wires Solutions

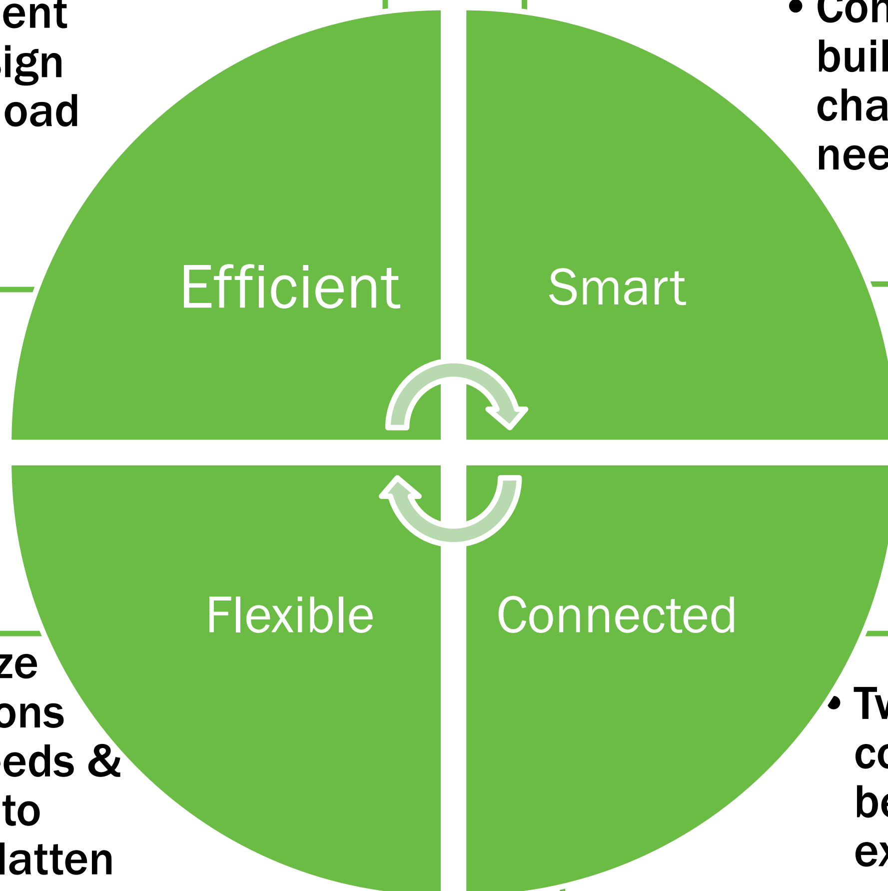
Load Shift
- Generation: Capacity
- T&D: Non-Wires Solutions

Modulate
- Frequency Regulation
- Ramping

Grid-interactive Efficient Buildings

- Efficient equipment and building design reduce building load

- Controls enable building load to change depending on needs and price



- Ability to optimize building operations per occupant needs & DER availability to offset, shift, or flatten building load

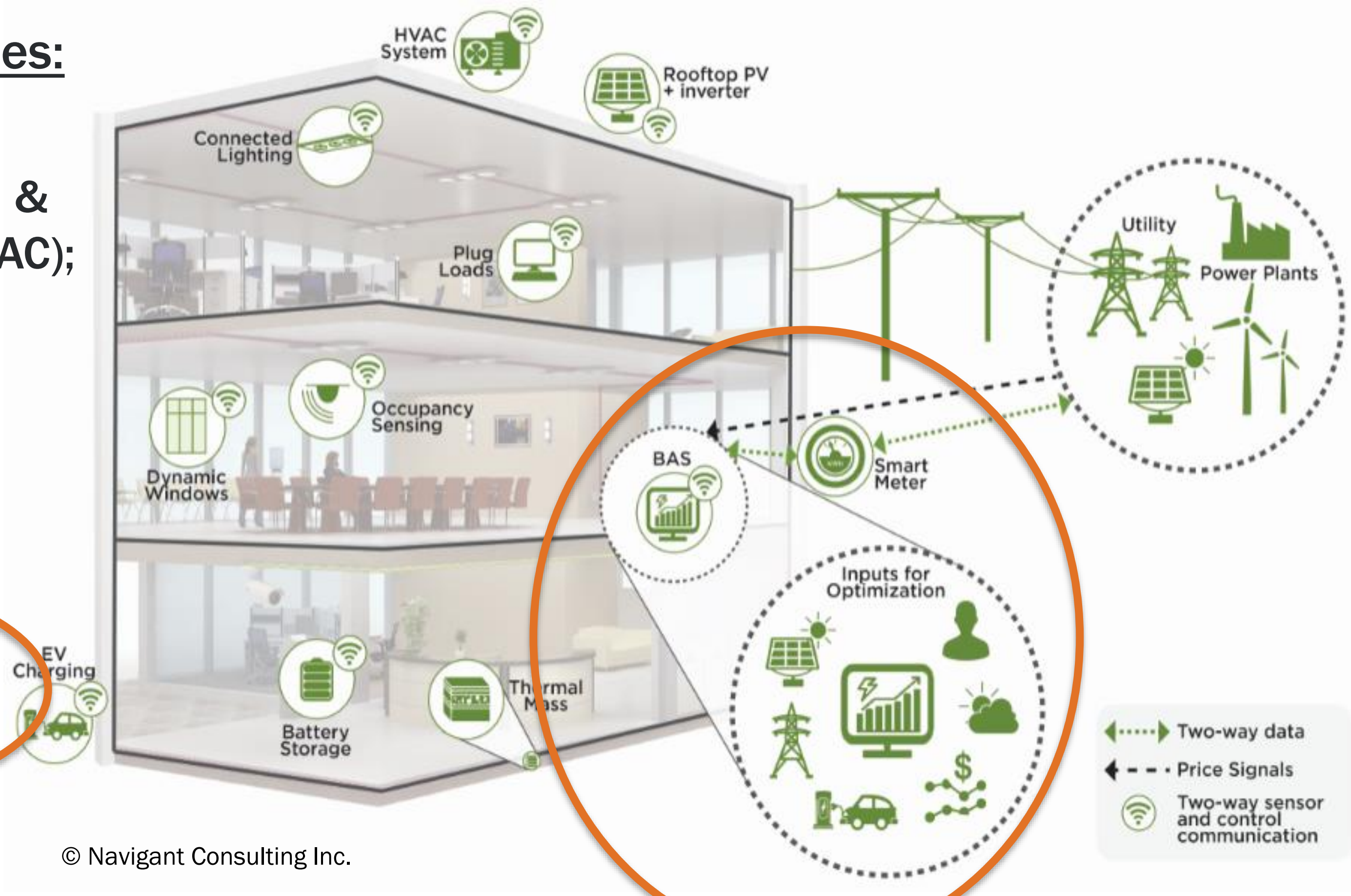
- Two-way communication flow between building and external entities

GEB Technical Report Series Overview

The GEB Technical Report Series will help guide BTO's R&D portfolio and serve as a foundational resource for the larger building research community.

<u>Technical Report Series:</u>

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



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GEB Modeling, Sensors, Controls, and Analytics

Report Summary

Why a combined report?

- **HVAC, Lighting, Windows & Envelope**
  - Focus on increasing demand flexibility capacity
- **Building Energy Modeling, Sensors, Controls, & Analytics**
  - How do we leverage that demand flexibility in practice?
  - How do we design for it?
  - How do we verify grid services provided?
  - How do we plan for large scale GEB deployment?

Cross-cutting Report Assumptions

- Slow- and fast-acting services can be decoupled
- The building level is the appropriate level of focus instead of device level
- GEB requires elastic financial modeling of occupant needs

Report Outline

Background

- Section 1 – Introduction
- Section 2 – Current State of Building Grid Services
- Section 3 – Grid Communications

Research Needs

- Section 4 – Execution
- Section 5 – Characterization
- Section 6 – Measurement and Verification
- Section 7 – Demand Flexibility Design
- Section 8 – Grid Planning
- Section 9 – Recommendation Summary

Setting The Stage

The Premise

- At a given level of EE, a building has some *demand flexibility* (DF) – shedding, shifting, modulating load

- Some key assumptions

Assumption I – Emphasize Shed & Shift

- **Working Theory**
  - Because modulating services both smaller in magnitude than shedding or shifting and occur at much higher frequencies, they are largely orthogonal to them
  - High-frequency services don't require traditional centralized control, sensing, or thermal modeling
- **AMIRITE?**

Assumption II – Internet of Buildings (IoB)

- **GEB is a challenging optimization & coordination problems best tackled at the building level**
  - Scalability
  - Security
  - Interoperability
  - Metering
  - End-Use Coordination
  - Overall System performance
- **That being said, distributed services likely to emerge first (and they already have) because of the cost-effectiveness**

- **Is this right? For which building types & grid services?**

Assumption III – Elastic Occupant Preferences

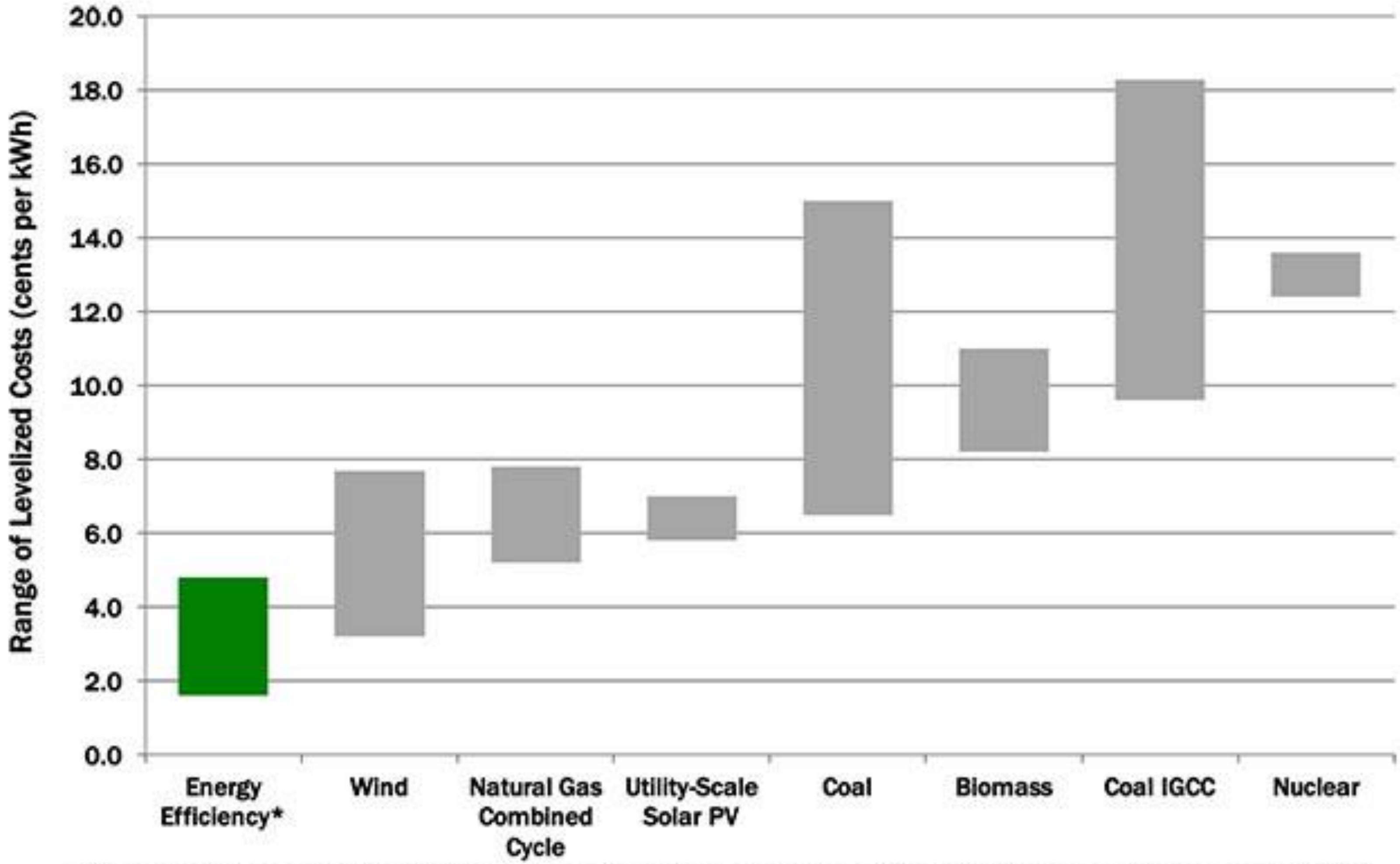
- Occupant preferences are not “vertical” constraints, they have price-sensitive supply demand curves

- Is this right? For what impacts?

Breaking Down the GEB Problem

- **Three phases of online GEB**
  - **Characterization** – what DF a building has, what it can offer when, in what amounts
  - **Execution** – delivering EE and grid services under changing conditions, while maintaining occupant comfort
  - **Verification** – demonstrating that grid services have been provided
- **Two offline activities**
  - **Design** – designing or retrofitting a GEB to activate and deploy demand flexibility
  - **Grid Planning** – large scale estimates of GEB capabilities for planning for building grid services as a grid resource
- **Not interested in online GEB from grid perspective**
  - That's a statistical problem

Section 2 – Current Building Grid Services



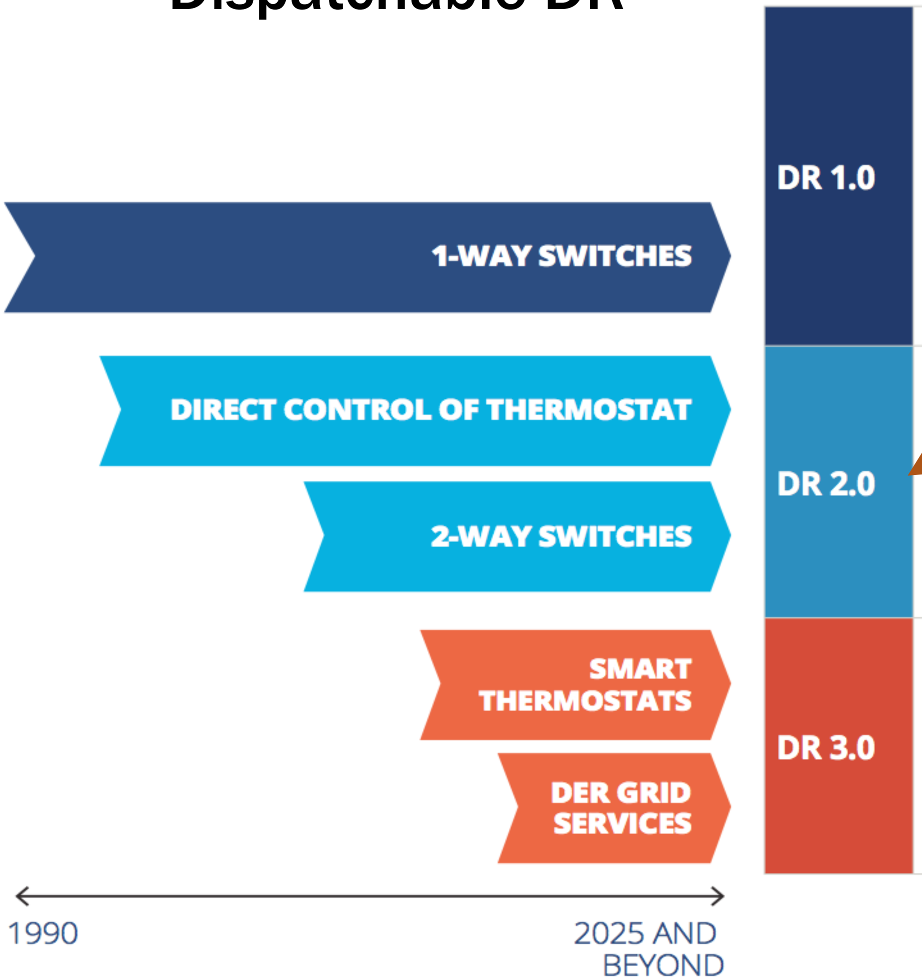
*Notes: Energy efficiency program portfolio data from Molina 2014; All other data from Lazard 2015. High-end range of coal includes 90% carbon capture and compression.

Section 2 – Current Building Grid Services

- **Energy Efficiency – the original grid service**
  - Generation
  - Capacity market
  - Grid reliability
    - Reducing peak demand
    - Easing T&D strain
    - Targeted "Non-wires alternatives"
  - Resource in IRP planning
  - Reduction in marginal line losses

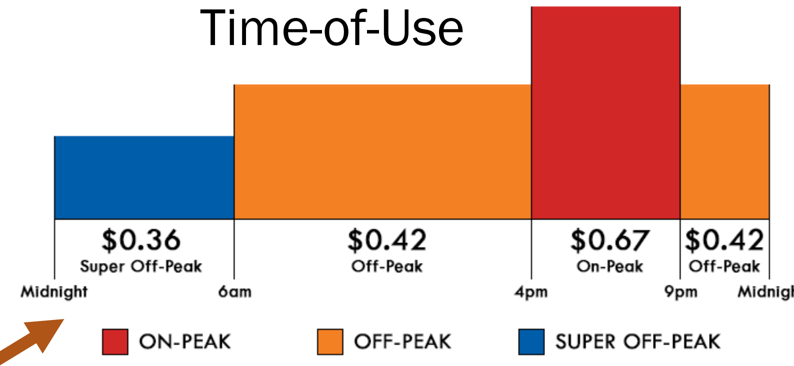
Section 2 – Current Building Grid Services

Dispatchable DR



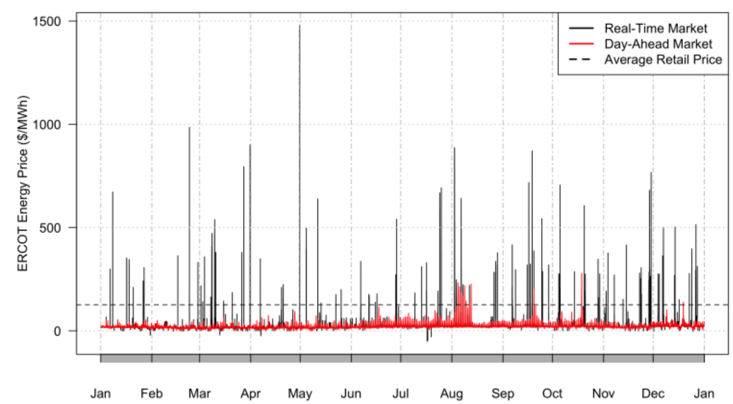
Source: Smart Electric Power Alliance, Navigant, and Peak Load Management Alliance[4], 2

Non-Dispatchable DR



https://solartechonline.com/blog/sdge-time-of-use-2019/

Real-time pricing



Section 3 – Grid Communications

- **DR communications: moving from one-way to two-way**
  - Allows smaller building participation in the market
- **Whole-sale markets – where grid services are currently bought and sold**
  - Buildings participate via aggregators, which pool the capabilities of many buildings
  - Moving to transactive markets could create additional flexibility in building participation
- **Interoperability – essential for seamless participation**
- **Cybersecurity – security needs at the device, building, and system level**

GEB Measurement & Verification

How does a GEB demonstrate the services provided?

M&V for EE

- **Flat-rate billing is basic M&V : meter measures voltage and current and uses those to calculate power and energy use**

- **For utility EE programs and for utility regulatory reporting, a counterfactual baseline is needed to which actual energy use can be compared**

- **Methods:**
  - Data-driven baseline from historical data (~6 months – 1 year)
  - Sub-metered data can support end-use M&V
  - BEM can also provide baseline when historic data are unavailable

M&V for DR

- **Variable-rate billing is basic M&V for (non-dispatchable) DR**
- **Consistent, cost-effective M&V for DR is still a need**

- **Methods:**
  - Day matching - same day from the prior week.
  - Previous days - using a weighted average from prior days
  - Weather correlation - using similar weather day from the past year

M&V for GEB

- Currently in which DR and EE are viewed as separate “regimes” with separate M&V procedures
- In the future, when a GEB delivers multiple grid services including EE, how can it even tell when it is doing DR as opposed to EE?
- Does the designation between EE and DR matter, or just the final provision of grid services?
- In particular, high frequency (i.e. modulating) and low frequency (i.e. shifting and shedding) services are orthogonal and can be delivered simultaneously due to the significant difference in these services’ temporal requirements

Baselines for GEB

- What is the most appropriate baselining method for GEB? Does it depend on service / context?

- How do we determine a baseline when multiple grid services are delivered?

- How can these baselines be continuously updated with the changing building/occupancy/weather contexts?

Secure Data Streams for GEB

- GEB M&V will be predicated on all parties (i.e. building and grid) agreeing to a "ground-truth" of current building conditions
- Today's sensors almost entirely lack embedded mechanisms for establishing rigorous trust in the data
- Sensor requirements (measurements, accuracy, frequency, reporting interval, etc.) have not been rigorously established
- Sensors and meters will need enough computing power to authenticate their own data, and create shared data repositories can enable multi-party access while protecting privacy.

GEB Execution:
How does GEB work in real time?

How Do EE & DR “Work” in Real Time?

- **Implementation**
  - Large commercial buildings: BAS
  - Homes: smart thermostats, Alexa
  - Small-medium commercial buildings: ?
- **EE architecture and algorithms**
  - Supervisory control + local control loops
  - Rules: 99.9999% (99.999999%?)
  - Model-predictive control (MPC)
- **DR**
  - Off/On Control
  - Direct or Autonomous

GEB >> EE + (A Lot Of) DR

- **EE + DR**
  - Baseline EE mode
  - Toggle to DR mode (completely disregard EE)
  - Return to EE mode → unintentional “recovery” spikes

- **GEB**
  - Continuous integrated optimization of EE and DR
  - Anticipate & prepare for DR
  - Smooth transitions, avoid recovery spikes
  - Minimize impact on occupants

Resolved: GEB is MPC. MPC is GEB.

- **Advance MPC fundamentals**
  - Modeling – white-box, black-box, gray-box, zebra-box?
  - Model training
  - Adaptivity
  - FDD
  - Interpretability
- **Tackle practical considerations**
  - Data acquisition
  - System integration
  - Configuration
  - Commissioning

GEB Specific – Objective Functions

- How to continuously balance EE & DR with building occupant & operator requirements & priorities?

GEB Specific – New/Advanced Actuation

- **Visibility & controllability beyond setpoints and on/off would expose more DF**
  - Opportunities at different levels
  - Supervisory: concurrent adjustment of set-points of multiple subsystems
  - Local loops: redesign to enable continuous adjustments at a wider range of time scales.
  - Equipment: multiple operating modes with different associated sets of set-points, including autonomous DR modes

GEB Specific – Uncertainty Management

- **Uncertainty in EE is almost always better than no EE**
- **Uncertainty in DF limits ability to estimate, commit & call**
- **Sources of uncertainty**
  - limited sensing and metering, limited availability of historical data, low data resolution, simplified EE models of buildings systems that do not capture dynamics such as equipment cycling, weather & occupancy forecasts
- **Control approaches**
  - passive -- robust or insensitive to uncertain parameters
  - active (adaptive) -- continually update uncertain parameters

General – Adaptivity

- **Types and amounts of DF in a GEB vary over time**
  - changing operating contexts, equipment degradation and faults, seasonal transitions, and changes in occupancy patterns and use
  - occupant preferences may vary throughout the year
  - equipment faults change baseline energy consumption and may alter the availability of DF

General – Interpretability

- **Rule based control systems are "expert systems" that follow human logic**
  - Allow human operators to supervise, verify & tune controls
- **Optimization methods may find non-intuitive solutions**
  - Difficult to follow the logic, trust and tune by hand
- **Interpretability options**
  - Map optimization onto rules
  - Ex post interpretability

Other Execution Questions

- Need to integrate "fast-acting" services?

Discussion MPC

- **Discussion points**
  - Objectives, time horizons
  - New and advanced actuation
  - Characterization, quantification and reduction of uncertainty of DF
  - Adaptive capabilities
  - Explainability and other barriers to adoption
  - Other control methods than MPC
  - MELS and equipment usage characterization
  - Shifting loads vs not-shifting loads, taxonomy
  - GEB relation to net zero energy objectives
  - System design for flexibility
  - Cyber security and risks for GEB
  - Autonomous operation provisions (lost connectivity); resiliency objectives
  - Prioritization of systems and research
  - Valuation of loss in service for occupants/owners vs productivity
  - Imperceptible effects on indoor conditions assured at all times
  - DF service will incur extra cost; can it come with extra value to comfort?
  - Impact on grid operation approach which now must account for uncertainty

Characterization

How to qualify, quantify & value DF

How are EE and DR Characterized

- **EE is not characterized in temporal detail**
  – Because it is not transacted in this way
  – Many well-established methods for EE characterization, both measured and modeled

- **DR is temporal, but not characterized at the building level (typically)**
  – Statistical methods characterize aggregated DR
  – Some context factors accounted for (e.g., outdoor temp)
  – Occupant impact is ignored

Three Aspects of DF Characterization

1. **Technical potential identification & quantification**
   – What forms of DF are physically available?
   – What are their characteristics? How “big” are they? What is the response time?

2. **Context specific estimation**
   – How much DF is actually available right now?
   – Based on occupancy, weather, past control decisions, etc.

3. **Valuation**
   – What are the occupant impacts of executing DF?
   – How do occupants value DF?
   – How do owners / operators value DF?

1. Technical Potential Quantification

- **Thermal loads**
  - Impute thermal time constants from measurements
    - Indoor temp, outdoor temp, solar, HVAC output
  - Need appropriate sensing & metering

- **Non-thermal loads**
  - Sub-metering – physical or virtual (NILM)
  - Self-assessing / self-reporting equipment?
  - Assessing typical flexibility based on historical usage patterns (at device or building level)

2. Context Specific Estimation

- **Essentially a forecasting problem**
  - Weather (including solar)
  - Occupancy and occupant needs
  - Grid conditions and needs

- **A GEB needs to understand the uncertainty around DF estimates based on these changing conditions**

3. Valuation

- **A GEB must package & present its DF availability to & integrate input from three groups of stakeholders**
  – DF availability varies due to control actions and external factors, GEB must periodically update and communicate its DF “model” (i.e. availability).
  – Occupants need information on expected discomfort and retain the ability to override certain DF decisions, when approved by building operators.
  – Input on comfort flexibility in a dynamic manner and at the time when their preferences and needs change.

<u>Key challenge:</u> Occupants’ preferences and valuations are often subjective, and they could be time-varying and scenario-driven. Surveys also might not fully and clearly articulate needs.

Valuation – Occupants

- **Shifting strategies that leverage thermal inertia or appliance scheduling may not be noticed by occupants**
  – Same for high-frequency services that modulate power consumption around an average value
- **Shedding can have dramatic impact on occupants and building function**
- **Challenge: Identifying & prioritizing devices whose use pattern can be altered without noticeable impact on occupants**

Valuation – Occupants (Continued)

- What value do occupants place on different forms of DF impact?
- How much do they want to be compensated in order to accept it?
- What impact will occupants not accept under any non-emergency circumstances?
- What is the right frequency and mode of interaction with building occupants?
- How much can be inferred from occupant actions and other proxies and how much must be asked explicitly and directly?

Valuation – Owners and Operators

- **Needs**
  - Information on building state, committed services, expected compensation, risk to not deliver on commitments & expected impact on occupants.
  - Implications on equipment degradation & maintenance & replacement costs.
  - Ability to prioritize certain grid services, to select particular systems & equipment that should participate & others that should not, regardless of their DF availability.

- **Challenges**
  - Quantify risk on building function and execution of commitments
  - Quantify impact of execution on equipment health & maintenance.
  - Quantify & forecast value of participation in grid services

Valuation – Grid Operators

- **GEB must compute and communicate its DF using models that resemble those for resources such as generation and storage, which can be readily used for grid operation and traded in electricity markets**
  - Concepts such as "virtual power plant", "virtual storage", "virtual battery", "packetized energy "

- **Challenge: DF models that can be aggregated over multiple buildings, and ensure privacy**

Offline Research Needs

Section 7: GEB Design

- **How do we (re)design GEBs to activate and deploy demand flexibility?**
  - Buildings can be co-designed for DF in the same way that they are currently designed for EE.
  - The tools and techniques for evaluating and optimizing DF in building design extend established EE design tools, primarily Building Energy Modeling.

- **Applications – same as EE:**
  - Designing and retrofitting
  - Building codes
  - Green Certification
  - Control Design

Section 7: GEB Design

- **Background:**
  - BEM is a major integrated design tool for EE
  - BEM is not used at all for DR design currently

- **Key question:**
  - Do fundamental changes need to be made to BEM engines to support GEB design?

Section 7: GEB Design

- **Controls Design – modeling real-world control sequences in BEM is important for improving EE design, and essential for DF design**

  – Spawn of Energy Plus: already under development for EE, but will have wide GEB applications

  – Will allow for holistic controls design, testing, and implementation

Section 7: Research Needs

1. **BEM Timestep:** the default 15-minute timestep in E+ is inadequate for modeling some plug loads and equipment cycling since steady-state operation is assumed within each timestep, thus poorly capturing real-world behavior and energy use in a granular way. For realistic GEB applications, either a more resolute timestep or a post-processed sub-timestep model should be superimposed on outputs.

2. **High-resolution stochastic inputs:** realistic occupancy in buildings leads to stochastic instantaneous power draws which are currently represented instead by standard schedules. Representing the stochastic nature of power draws is important for accurate estimation of future GEB performance and for rolling up into stock models for utility program planning. .

Section 7: Research Needs

3. **GEB Output Metrics:** extension of BEM performance metrics to GEB(e.g. TDV for other areas, GridOptimal) as well as new GEB-adjacent metrics such as survivability. Identifying the appropriate metrics is the main research question instead of implementation.

4. **Control Sequences and Interfaces:** Future GEBs will have to be designed, rated, and otherwise evaluated in the context of MPC. Incorporating real-world control sequences will be essential for designing GEBs with DF capabilities.

Section 7: Research Needs

5. **Electrical Modeling:** BEM engines only calculate real power, but some grid services—especially high-frequency and distribution level grid services—rely on reactive power or specific power characteristics such as voltage and frequency. It's unlikely that these will need to be incorporated at the building level, but component models or post-processing might support inclusion of electrical characteristics in BEM.

6. **District Systems:** By coordinated control of multiple buildings, the district system has significant potential to shift or shed load as needed, with minimal disruption to the occupants. Most BEM tools currently do not model district thermal systems .

Section 7: Research Needs

7. **Co-Simulation:** Linking building models with other system models has the potential to provide increased system energy efficiencies than designing each independently. Examples: electrical distribution, transportation, microgrids, community solar/storage. For each of these, there is a need to explore whether loosely or tightly-coupled models will be more appropriate (and this might be application-dependent)

Section 8: Grid Planning

- **How do utilities and grid operators plan for using building services as a grid resource?**
  - Forecasting
  - Utility programs
  - Integrated distribution system planning

- **There's a need for models and methods to estimate demand flexibility at scale.**
  - Stock models (BEM)
  - Data-driven models

Section 8: Research Needs

1. **End-Use Load Profiles and Savings:** regional-specific representations of end-use consumption to support load forecasting, IRP, rate design, and aggregate DF estimation .

2. **Future Weather:** DF is more weather-dependent than traditional EE applications as weather because of GEB's reliance upon factors such as external temperature and cloud cover. In the future, weather could be significantly different than it is in the past, so both building design and grid planning will need improved models of future weather parameters

Section 8: Research Needs

3. **Building Stock Models:** physics-based stock models are being used in an increasing number of utilities for program design and scenario forecasting. To continue to support GEB applications, stock models should improve speed, accuracy, and user experience.

4. **Data-driven estimation methods:** physics-based models will be limited in applicability for many high-frequency GEB applications. They also currently lack information on electrical system characteristics. Data-driven models on could fill these holes and also support other applications like short-term load forecasting.

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