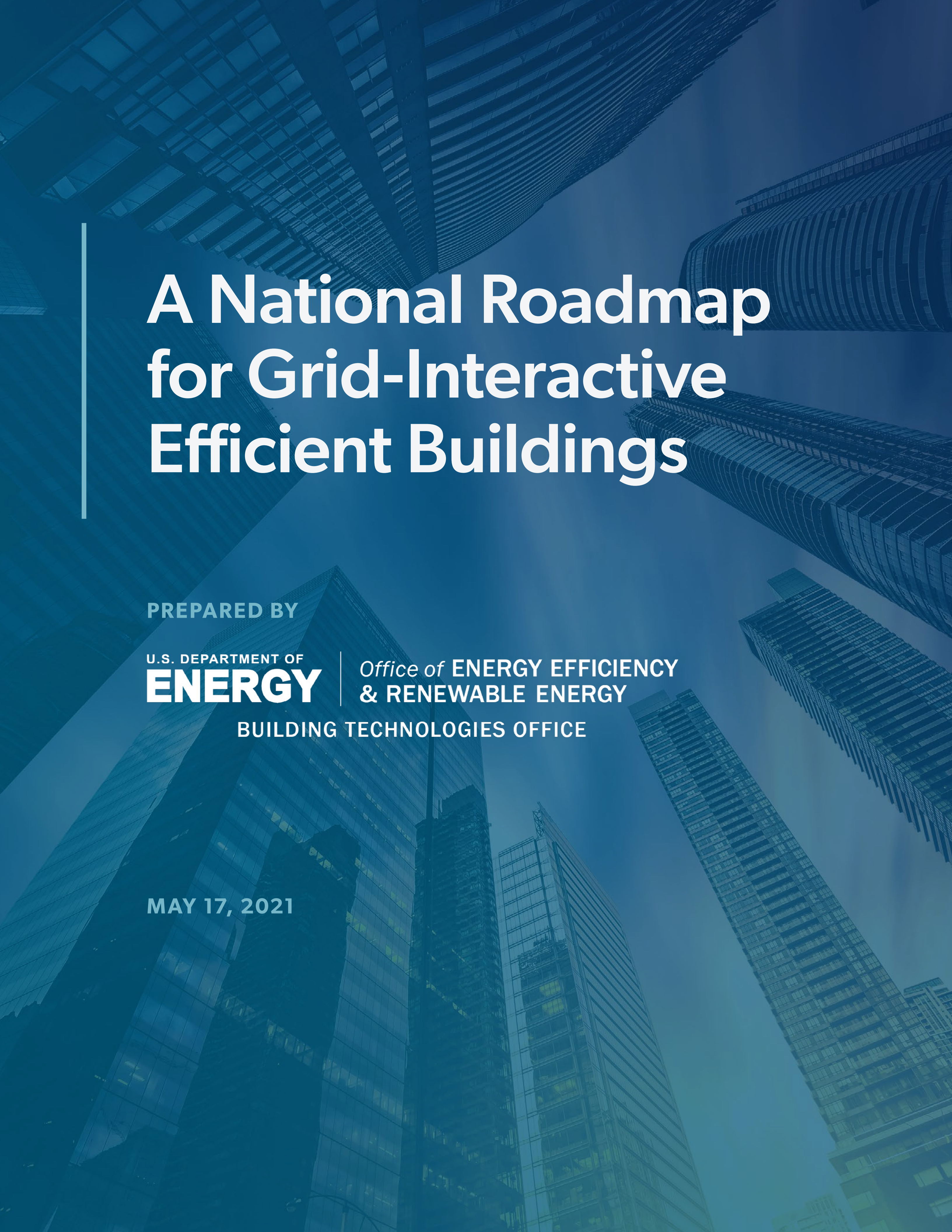


# A National Roadmap for Grid-Interactive Efficient Buildings

PREPARED BY


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

BUILDING TECHNOLOGIES OFFICE



MAY 17, 2021

# AUTHORS


## Lawrence Berkeley National Laboratory

Andrew Satchwell

Mary Ann Piette

Aditya Khandekar

Jessica Granderson

Natalie Mims Frick

## The Brattle Group

Ryan Hledik

Ahmad Faruqui

Long Lam

Stephanie Ross

Jesse Cohen

## Energy Solutions

Kitty Wang

Daniela Urigwe

## Wedgemere Group

Dan Delurey

## U.S. Department of Energy

Monica Neukomm

David Nemtzow

## ACKNOWLEDGMENTS

The work described in this study was funded by the U.S. Department of Energy (DOE) Building Technologies Office (BTO) under Lawrence Berkeley National Laboratory (LBNL) Contract No. DE-AC02-05CH11231. The authors would like to acknowledge the valuable guidance and input provided during the preparation of this report. The authors are also grateful to the following list of contributors. Their feedback, guidance, and review proved invaluable in preparing this report. Any remaining errors or omissions are our own.

We are grateful to the project's Technical Advisory Group for valuable guidance during the scoping phases and for thoughtful review of the final report. Members of the Technical Advisory Group were Clay Nesler (Alliance to Save Energy), Greg Wikler (California Efficiency + Demand Management Council), John Taylor (Consortium for Energy Efficiency), Ram Narayanamurthy (Electric Power Research Institute), Adam Cooper (Institute for Electric Innovation), Danielle Sass Byrnett (National Association of Regulatory Utility Commissioners), Rodney Sobin (National Association of State Energy Officials), David Terry (National Association of State Energy Officials), Giselle Procaccianti (Northeast Energy Efficiency Partnerships), Susan Stratton (Northwest Energy Efficiency Alliance), Richard Philip (Peak Load Management Alliance), Ann McCabe (Regulatory Assistance Project), Mark Dyson (Rocky Mountain Institute), Cara Carmichael (Rocky Mountain Institute), and Aaron Smallwood (Smart Electric Power Alliance).

The modeling in this report built on extensive analysis of the technical potential for grid-interactive efficient buildings conducted by researchers at LBNL and the National Renewable Energy Laboratory (NREL), and leveraged output from NREL's Standard Scenarios power grid simulations. We thank Jared Langevin (LBNL), Chioke Harris (NREL), Pieter Gagnon (NREL), Aven Satre-Meloy (LBNL), Handi Chandra Putra (LBNL), Andrew Speake (NREL), Elaina Present (NREL), Rajendra Adhikari (NREL), and Eric Wilson (NREL).

This report benefitted from detailed, thoughtful review by the following individuals: Rachel Gold (American Council for an Energy-Efficient Economy (ACEEE)), Dan York (ACEEE), Hannah Bastian (ACEEE), Christopher Perry (ACEEE), Laura Van Wie McGrory (Alliance to Save Energy), John Taylor (Consortium for Energy Efficiency), Cedar Blazek (DOE), Ryan Fedie (DOE), Johanna Zetterberg (DOE), Madeline Salzman (DOE), Ookie Ma (DOE), Jack Mayernik (DOE), Erika Gupta (DOE), Philip Coleman (Federal Energy Management Program/LBNL), Debyani Ghosh (Guidehouse), Tom Eckman (Independent Consultant), Brian Gerke (LBNL), Lisa Schwartz (LBNL), Lou Sahlu (MA DOER), Hanna Terwilliger (Minnesota PUC), Giselle Procaccianti (Northeast Energy Efficiency Partnerships), Eric Wilson (NREL), Nikitha Radhakrishnan (PNNL), Jason Salmi Klotz (Portland General Electric), David Farnsworth (RAP), Aaron Smallwood (SEPA), Jeannette LeZaks (Slipstream), Maddie Koolbeck (Slipstream), Joe Zhou (Slipstream), Lee Shaver (Slipstream), and Lauren Morlino (Vermont Energy Investment Corporation).

For additional research contributions, we thank Sharan Ganjam (The Brattle Group), Pearl Donohoo-Vallett (The Brattle Group), Rohini Srivastava (ACEEE), and Mary Shoemaker (ACEEE). We also thank Brattle's Marketing team for technical editing and graphical layout of the report.

Additionally, this report was informed by in-depth interviews with a wide range of industry experts, as well as input provided during a series of workshops with building technologies experts from DOE and the National Labs. Please see Appendices D and E of this report for lists of individuals and organizations that participated in those activities.

## LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| **ACEEE** | American Council for an Energy-Efficient Economy |
| **AEO** | Annual Energy Outlook |
| **ADR** | Automated Demand Response |
| **AMI** | Advanced Metering Infrastructure |
| **ANSI** | American National Standards Institute |
| **API** | Application Programming Interface |
| **APS** | Arizona Public Service |
| **ARRA** | American Recovery and Reinvestment Act |
| **ASHRAE** | American Society of Heating, Refrigerating and Air-Conditioning Engineers |
| **AVERT** | AVoided Emissions and geneRation Tool |
| **BA** | Balancing Area |
| **BAS** | Building Automation System |
| **BTO** | Building Technologies Office |
| **CAC** | Central Air Conditioning |
| **CAISO** | California Independent System Operator |
| **CALCTP** | California Advanced Lighting Controls Training Program |
| **CBS** | Consumer Behavior Studies |
| **CEC** | California Energy Commission |
| **CHIP** | Connected Home over IP |
| **CONE** | Cost of New Entry |
| **CPP** | Critical Peak Pricing |
| **CSRP** | Commercial System Relief Program |
| **CTA** | Consumer Technology Association |
| **DOE** | U.S. Department of Energy |
| **DER** | Distributed Energy Resource |
| **DERMS** | Distributed Energy Resource Management System |
| **DF** | Demand Flexibility |
| **DLC** | Direct Load Control |

| | |
|---|---|
| **DR** | Demand Response |
| **DRP** | Distribution Resource Plan |
| **DRQAT** | Demand Response Quick Assessment Tool |
| **DSM** | Demand-Side Management |
| **DSRP** | Distribution System Relief Program |
| **EE** | Energy Efficiency |
| **EEI** | Edison Electric Institute |
| **EDF** | Environmental Defense Fund |
| **EIA** | Energy Information Administration |
| **EMM** | Electricity Market Module |
| **EMIS** | Energy Management Information System |
| **EM&V** | Evaluation, Measurement, and Verification |
| **ERCOT** | Electric Reliability Council of Texas |
| **ESCO** | Energy Services Company |
| **ESPC** | Energy Savings Performance Contracting |
| **EPA** | Environmental Protection Agency |
| **FERC** | Federal Energy Regulatory Commission |
| **GEB** | Grid-Interactive Efficient Building |
| **GHG** | Greenhouse Gas |
| **GSA** | General Services Administration |
| **GW** | Gigawatt |
| **HECO** | Hawaiian Electric Companies |
| **HPWH** | Heat Pump Water Heater |
| **HTML** | Hypertext Markup Language |
| **HTTP** | Hypertext Transfer Protocol |
| **HVAC** | Heating, Ventilation, and Air Conditioning |
| **ICT** | Internet Controlled Thermostat |
| **ICAP** | Installed Capacity |
| **IDSM** | Integrated Demand-Side Management |

| | |
|---|---|
| **IP** | Internet Protocol |
| **IRP** | Integrated Resource Planning |
| **ISO** | Independent System Operator |
| **LBNL** | Lawrence Berkeley National Laboratory |
| **LEED** | Leadership in Energy and Environmental Design |
| **LMI** | Low-to-Moderate Income |
| **LRAM** | Lost Revenue Recovery Mechanism |
| **MISO** | Midcontinent Independent System Operator |
| **MEL** | Miscellaneous Electric Load |
| **MPC** | Model Predictive Control |
| **MW** | Megawatt |
| **NARUC** | National Association of Regulatory Utility Commissioners |
| **NASEO** | National Association of State Energy Officials |
| **NEEP** | Northeast Energy Efficiency Partnership |
| **NPV** | Net Present Value |
| **NREL** | National Renewable Energy Laboratory |
| **NYISO** | New York Independent System Operator |
| **NWS** | Non-Wires Solutions |
| **PBR** | Performance-Based Regulation |
| **PGE** | Portland General Electric |
| **PLMA** | Peak Load Management Alliance |
| **PNNL** | Pacific Northwest National Laboratory |
| **PUC** | Public Utilities Commission |
| **PV** | Photovoltaics |
| **RFP** | Request for Proposal |
| **RMI** | Rocky Mountain Institute |
| **RPS** | Renewable Portfolio Standard |
| **RTO** | Regional Transmission Organization |
| **RTP** | Real-Time Pricing |

| | |
|---|---|
| **SB** | Senate Bill |
| **SCE** | Southern California Edison |
| **SEPA** | Smart Electric Power Alliance |
| **SGIG** | Smart Grid Investment Grant |
| **SHEMS** | Smart Home Energy Management System |
| **SMUD** | Sacramento Municipal Utility District |
| **SPP** | Southwest Power Pool |
| **SWEEP** | Southwest Energy Efficiency Project |
| **TCP** | Transmission Control Protocol |
| **T&D** | Transmission and Distribution |
| **TES** | Thermal Energy Storage |
| **TOU** | Time of Use |
| **TRL** | Technology Readiness Level |
| **UCAP** | Unforced Capacity |
| **VFD** | Variable Frequency Drive |
| **VPP** | Variable Peak Pricing |
| **WECC** | Western Electricity Coordinating Council |

## CONTENTS

## APPENDICES

## FIGURES

## TABLES

## FROM THE DIRECTOR

Dear Colleagues,

Since Thomas Edison threw the switch at the world's first commercial power plant in 1882 to power 400 lamps, buildings have consumed the lion's share of U.S. electricity, and today account for three-fourths of the total and even more at peak. Yet, buildings consume power indifferent to grid conditions, blind to the high costs and threats to reliability posed by high peak demand and grid stress; inflexible to opportunities offered by variable, carbon- free renewable power sources; and senselessly missing the smart and connected technology revolution.

**Grid-interactive efficient buildings (GEBs)** can remake buildings into a major new clean and flexible energy resource. GEBs combine energy efficiency and demand flexibility with smart technologies and communications to inexpensively deliver greater affordability, comfort, productivity, renewables integration and high performance to America's homes and commercial buildings.

The stakes could not be higher for the U.S. and for power consumers; national adoption of GEBs brings new value measured in the hundreds of billions of dollars over the coming two decades. Given the enormous untapped opportunity, the U.S. Department of Energy (DOE) is announcing a national goal for GEBs: **To triple the energy efficiency and demand flexibility of the buildings sector by 2030 relative to 2020 levels.**

This *Roadmap* includes 14 key recommendations that should be taken by a broad array of market and policy actors. We recommend:

- Advancing GEBs through R&D to improve technology interoperability and integration, along with specific hardware improvements;
- Enhancing and communicating the value proposition of GEBs to consumers, utilities, aggregators, grid operators and regulators;
- Empowering users, installers and operators by developing tools that co-optimize energy, non-energy and financial benefits, and training workers on these innovative technologies;
- Using federal, state and local government actions for GEB deployment, including "leading by example" with government buildings, expanding funding and financing, setting codes and standards and establishing targets.

Action can begin ***immediately*** on each recommendation, with completion of the most significant implementation activities feasible within two years. DOE stands ready to work with those who share our vision to champion an affordable, reliable, clean and productive future for the U.S.'s buildings and power grid.

Sincerely,

David Nemtzow

**David Nemtzow**
Director, DOE Building Technologies Office

# Executive Summary

Buildings account for more than 70% of U.S. electricity use and at least one-third of U.S. economy-wide $CO_2$ emissions. Improving the way electricity is consumed and reducing the overall amount of electricity consumption in buildings would significantly reduce energy costs to consumers and facilitate the transition to a decarbonized economy.

**Grid-interactive efficient buildings (GEBs)** are energy-efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to optimize energy use for grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way. In doing so, GEBs can play a key role in promoting greater affordability, resilience, environmental performance, and reliability across the U.S. electric power system.

Over the next two decades, national adoption of GEBs could be worth between $100–200 billion in U.S. electric power system cost savings. By reducing and shifting the timing of electricity consumption, GEBs could decrease $CO_2$ emissions by 80 million tons per year by 2030, or 6% of total power sector $CO_2$ emissions. That is more than the annual emissions of 50 medium-sized coal plants, or 17 million cars.

**DOE's National Goal for GEBs: Triple the energy efficiency and demand flexibility of the buildings sector by 2030 relative to 2020 levels.**

However, technical and market barriers at each point in the GEB value chain are impeding these benefits from being realized. Technological advancements are needed to overcome challenges related to interoperability and cybersecurity concerns, and to provide deeper and more reliable load impacts. Successful deployment of these technologies will require addressing insufficient workforce training and financial opportunities among firms with installation and implementation responsibility.

Consumer adoption of this technology will require overcoming a lack of consumer awareness of participation incentives, mitigating perceived risks (e.g., complexity), and addressing insufficient participation incentive levels. Similarly, the utilities and other entities responsible for operationalizing the technology benefits – to reduce system costs and emissions – currently lack regulatory models necessary to fully consider GEBs as an alternative to other resource investments. Additionally, policymakers and regulators often lack the information or awareness of opportunities they need in order to facilitate GEB advancements, or otherwise the desire to do so.

Nevertheless, these barriers can be overcome. This *Roadmap* provides 14 recommendations for addressing the top barriers to GEB adoption and deployment (see **TABLE 1**). Action can begin immediately on each recommendation,

| ROADMAP PILLAR | RECOMMENDATION |
| --- | --- |
| 1. Advancing GEBs Through Research, Development, and Data | Develop/accelerate deployment of GEB technologies |
| | Accelerate technology interoperability |
| | Improve access and use of DF data |
| 2. Enhancing the Value of GEBs to Consumers and Utilities | Develop innovative incentive-based programs |
| | Expand price-based program adoption |
| | Introduce incentives for utilities to deploy demand-side resources |
| | Incorporate DF into resource planning |
| 3. Empowering GEB Users, Installers, and Operators | Understand user interactions with GEBs and role of tech |
| | Develop GEB design & operation decision-making tools |
| | Integrate smart technology training into existing programs |
| 4. Supporting GEB Deployment Through Federal, State, and Local Enabling Programs and Policies | Lead by example |
| | Expand funding and financing options |
| | Consider use of codes & standards |
| | Consider implementing state targets or mandates |

**TABLE 1:** ROADMAP RECOMMENDATIONS

with completion of the most significant implementation activities being feasible within the next two years.

These recommendations come with particular urgency given the anticipated growth in adoption of DERs such as electric vehicles, solar PV, and energy storage. The GEB vision requires not only improving the efficiency and flexibility of dominant building loads that exist today, but also preparing to integrate valuable new, decarbonized sources of load and generation into building and grid operations.

Making GEB opportunities accessible to low-income and underserved communities will be an important consideration in these initiatives. The recommendations in this *Roadmap* include steps that are specifically oriented toward removing barriers to equity and inclusion in GEB adoption. For example, considerations include reducing up-front technology costs and increasing engagement with underrepresented consumer segments.

Implementing the *Roadmap* recommendations will require coordination across all major industry stakeholder groups. Strong leadership from within a diverse mix of organizations is needed. As such, GEBs can provide career-defining opportunities for "champions" of more efficient and flexible electricity consumption. As the U.S. power system continues its rapid transition over the coming decade and beyond, buildings will be central to ensuring that the transition is affordable, reliable, and clean.

# I. Introduction

## Why Grid-Interactive Efficient Buildings?

The way electricity is generated and consumed in the U.S. is quickly changing. The rapidly growing use of wind and solar is leading to a more variable power generation resource mix. Electric vehicles sales are increasing and are projected to become a significant new electric load. Greater investment will be needed to replace the aging transmission and distribution infrastructure that delivers this electricity to consumers, let alone to keep up with the electricity delivery needs of a modernized grid. Increasing reliance on electricity will impose new demands on the power system. Further, many consumers are generating or storing their electricity on-site, making two-way flows more common on the power grid.

A robust portfolio of flexible and cost-effective resources will be needed to address the challenges that these changes represent. This portfolio will be a mix of generation, demand-side, and storage resources. Most importantly, the U.S. is quickly focusing on the need to reduce, if not eliminate,[1] $CO_2$ emissions that result from the electricity sector.

One important opportunity is better coordinating electricity consumption in residential and commercial buildings with grid needs and resources. Buildings account for over 70% of all U.S. electricity consumption[2] and at least one-third of U.S. economy-wide emissions.[3] For decades, targeted efforts have improved the efficiency of energy consumption in these buildings. Additionally, the load of some buildings has been managed in order to reduce electric power use during times of peak electricity demand, when the grid is most stressed, most expensive to operate, and often has the highest $CO_2$ emissions.

Yet, there are opportunities to better coordinate building electricity use, particularly integrating the growing number of DERs with grid conditions to address the evolving challenges on the power system. Consumer adoption of new energy technologies will introduce opportunities for improving the efficiency and flexibility of electricity consumption while better serving the needs of building owners and occupants, as well as benefiting the broader distribution system.

**Grid-interactive efficient buildings (GEBs)** are energy-efficient buildings with smart technologies characterized by the active use of DERs to optimize energy use for grid

1 More details on the Biden Climate Plan can be found here: https://joebiden.com/climate-plan/.

2 U.S. Energy Information Administration, Form 861, 2019.

3 Jared Langevin, Chioke B. Harris, and Janet L. Reyna (2019), "Assessing the Potential to Reduce U.S., Building CO2 Emissions 80% by 2050." Joule 3, 2403-2424.

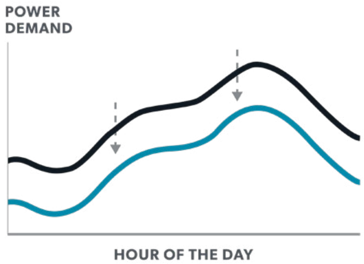
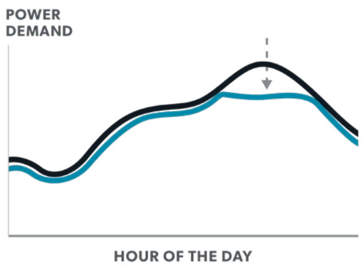
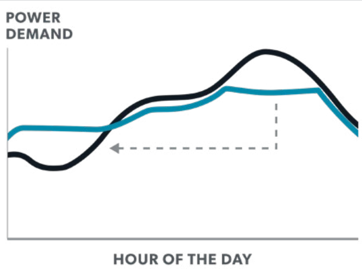
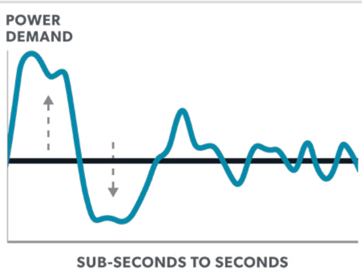
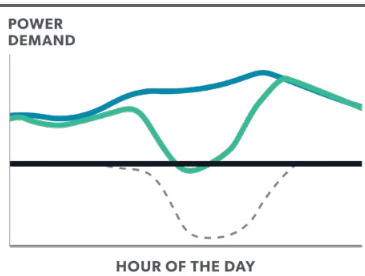
| | LOAD IMPACT | EXAMPLE MEASURE | EXAMPLE BENEFIT |
|---|---|---|---|
| **Efficiency** |   | Building has an insulated, tight envelope and an efficient HVAC system to reduce heating/cooling energy needs | Reduced costs of burning fuel to satisfy energy demand, and reduced emissions associated with lower fuel use |
| **Shed Load** |   | Building dims lighting system by a preset amount in response to grid signals while maintaining occupant visual comfort levels | Reduced investment in generation and transmission capacity due to lower peak demand |
| **Shift Load** |   | Connected water heaters pre-heat water during off-peak periods in response to grid signals | Reduced energy costs due to shifting consumption to cheaper hours of the day; avoided curtailment of renewables during off-peak periods |
| **Modulate** |   | Batteries and inverters autonomously modulate power draw to help maintain grid frequency or control system voltage | Reduced ancillary services costs, improved integration of variable generation resources (e.g., wind, solar) |
| **Generate** |   | Rooftop solar PV exports electricity to the grid | Reduced T&D losses due to on-site consumption; avoided need for grid-scale generation |

**TABLE 2:** WAYS IN WHICH GEBs CAN PROVIDE VALUE TO THE GRID

services, occupant needs and preferences, climate mitigation, and cost reductions in a continuous and integrated way.[4] In doing so, GEBs can play a key role in promoting greater affordability and reliability across the U.S. power system. Further, GEBs can reduce greenhouse gas emissions through lower overall energy use and increased flexibility of demand, which facilitates the integration of renewable generation. The ways in which GEBs can provide grid services are summarized in **TABLE 2**.

GEBs provide value directly to the electricity consumer as well. The grid benefits described above reduce system costs, which, in addition to lower electricity consumption, should ultimately translate into lower bills for consumers. System reliability improvements resulting from demand flexibility are also a consumer benefit. Additionally, GEBs can improve the satisfaction of building owners and occupants by increasing choice, resiliency, and flexibility in how electricity is consumed, and in some cases, improving the overall comfort of building occupants.

## Purpose of the *Roadmap*

The U.S. Department of Energy (DOE) Buildings Technologies Office (BTO) has a mission to support the research and development (R&D), validation, and integration of affordable, energy-saving technologies, techniques, tools, and services for buildings (both existing and new, residential and commercial). In support of this mission, BTO has developed a *Roadmap* that identifies the most important barriers and outlines the key opportunities for full implementation of GEBs and associated demand flexibility. Specifically, this *Roadmap* addresses the following objectives:

- Estimate the **value of the untapped GEB opportunity** to the power system.
- Define GEB technology **attributes and integration considerations.**
- Identify and prioritize **barriers** to GEB deployment and to achieving the untapped potential.
- Recommend **options for overcoming the barriers** with "action steps" for all key industry stakeholders.

The *Roadmap* is designed to recognize that there are many possible paths to increasing GEB adoption. Stakeholders[5] are likely to implement a patchwork of approaches that reflect the unique regulatory, legislative, and market conditions among states, municipalities, utilities, and customers. The ultimate intent of the *Roadmap* is to present key actions that could be taken by a wide range of industry stakeholders to access untapped GEB opportunities.

## FAQs About the *Roadmap*

- **Which consumer segments are included in GEBs?** By definition, GEBs are residential and commercial buildings. Industrial facilities are outside the scope of this *Roadmap*, as are data centers, transportation, and agricultural loads, though they are an additional and important source of energy efficiency (EE), DERs, and demand flexibility.
- **How do GEBs integrate DERs?** This *Roadmap* discusses DERs with a particular focus on the efficiency and active management of electricity that is consumed by end-users in a building. The integration of DERs within a building or across multiple buildings is an emerging area of GEB

4 U.S. DOE, "Grid Interactive Efficient Buildings: Overview," prepared by Monica Neukomm, Valerie Nubbe, and Robert Fares, April 2019.

5 "Stakeholders" includes building owners/occupants (including tenants, managers, and energy managers), demand flexibility aggregators and energy services companies, the federal government (primarily DOE and FERC), building energy technology implementation and installation firms, wholesale market operators, policy advocacy organizations, research organizations, state and local governments (including regulatory commissions and other agencies), technology developers, appliance manufacturers, and utilities.

research, reflected in DOE's advanced controls research[6] and Connected Communities projects.[7] Section 3 highlights opportunities and research questions specific to DER integration with GEBs; an important next phase of BTO's research and analysis will focus on the integration of DERs, including energy storage, distributed generation, and EVs.

- **What is demand flexibility?** Demand flexibility, also sometimes referred to as load flexibility, is the capability provided by on-site DERs to reduce, shed, shift, modulate, or generate electricity. *Building* demand flexibility specifically represents the capability of controls and end-uses that can be used, typically in response to price changes or direct signals, to provide benefits to buildings' owners, occupants, and to the grid.
- **What time horizon is considered in the *Roadmap*?** The *Roadmap* focuses on identifying the value of the GEB opportunity over the coming decade (i.e., through 2030) and actions that can be taken immediately to begin to realize this value.
- **Who is the intended audience for this Roadmap?** The *Roadmap* includes actionable recommendations for all electricity industry stakeholders with a potential interest in GEBs.

## Organization of the *Roadmap*

The remainder of this *Roadmap* is organized as follows:

Chapter 2 presents an assessment of the national and regional value that a portfolio of GEBs could provide to the power system, including a brief overview of the modeling methodology. This is followed by a summary of findings regarding GEB value, as well as measure-specific insights.

Chapter 3 lays out a vision for GEB development, followed by descriptions of specific GEB technologies and a discussion of technology integration within a building. The chapter concludes with important considerations related to the integration of electric vehicles, solar PV, and energy storage systems into buildings.

Chapter 4 describes the most significant barriers to GEB technology deployment and adoption, with a focus specifically on the most significant barriers at each point in the GEB value chain.

Chapter 5 presents 14 recommendations for overcoming the barriers described in Chapter 4. The recommendations are organized around four "pillars" of GEB deployment. Action steps are discussed for each stakeholder in the GEB value chain.

Chapter 6 concludes the *Roadmap* with a discussion of the conditions necessary to put the Roadmap's recommendations into action, and sets the stage for subsequent analysis of GEB benefits focused on the building integration of additional DERs.

Several technical appendices describe additional modeling detail and stakeholder engagement activities that supported the development of this *Roadmap.*

6 U.S. DOE website: https://www.energy.gov/eere/buildings/sensors-and-controls.

7 U.S. DOE website: https://www.energy.gov/eere/articles/can-connected-communities-solve-grid-challenges-scale-let-s-find-out.


# 2. The $100 Billion GEB Opportunity

## Introduction

Chapter 2 presents an analysis of the gross benefits that GEBs could provide to the U.S. electric power system by 2030, given an achievable level of deployment. Overall, the analysis finds that the U.S. electric power system benefits of GEBs could amount to between $8 billion and $18 billion annually by 2030, or 2–6% of total U.S. electricity generation and transmission costs projected by the EIA in 2030.[8] The cumulative power system benefits from 2021 to 2040 could reach $100 billion to $200 billion.[9] These financial savings could be accompanied by significant environmental benefits, with annual $CO_2$ emissions reductions reaching 80 million tons (i.e., about 6% of total power sector emissions) by 2030. It is equivalent to the annual emissions of more than 50 medium-sized coal plants or 17 million cars.[10]

The estimated power system benefits of GEBs are based on hourly EE and demand flexibility technology performance, and power system marginal costs and emissions. The EE measures considered in this analysis reduce electricity consumption relative to a baseline technology (see efficiency row in **TABLE 2**), while the demand flexibility measures are capable of daily load shifting or shedding (see **TABLE 2**). EE measures represent the most energy-efficient commercially available options today (e.g., a high-efficiency air-conditioner); demand flexibility measures are enabled by control technologies (e.g., a smart thermostat). Demand flexibility from "behavioral" or "manual" consumer actions is not considered. This study does not broadly include DERs such as rooftop solar, battery storage, backup generators, and other technologies that generate or discharge electricity, as well as electric vehicle charging load. Developing building load profiles that reflect the impacts of key DERs is an important next step to more comprehensively analyze and integrate the GEB potential of these emerging resources.

Importantly, the power system benefits quantified in this analysis are consistent with historical, achievable levels of technology adoption, based on a detailed review of market research studies and utility experience with demand

8 Calculated using data from EIA's 2020 Annual Energy Outlook (AEO), Table 8.

9 Benefits do not net out GEB technology costs. All savings estimates are presented in 2019 dollars. $100–200 billion reflects the NPV at a social discount rate of 4% nominal (2% real). Because this study informs climate change-related policymaking we believe a social discount rate is more appropriate than one based on a company's cost of capital. While there is considerable debate in the literature on what constitutes an appropriate social discount rate, we chose 2% real based on a survey of 200 experts conducted by the London School of Economics (available at: https://www.lse.ac.uk/granthaminstitute/explainers/what-are-social-discount-rates/).

10 The power plant comparison assumes 350 MW per coal plant, coal heat content of 97 kg/MMBtu (average subbituminous coal value reported by EIA, July 2020), average heat rate of 10.6 MMBtu/MWh (Form EIA-923, 2019 value), and annual capacity factor of 48% (Form EIA-923, 2019 value). The car comparison assumes 4.6 metric tons $CO_2$ per passenger vehicle per year, as per EPA website.

| | | |
|---|---|---|
| 1 | **Define GEB measures** to represent the best commercially available technology for major building end-uses. | **LBNL/NREL analysis** |
| 2 | **Simulate GEB technology performance** for thousands of individual buildings on an 8,760 hourly basis. | **NREL's ResStock & DOE's Commercial Prototype models** |
| 3 | **Scale building characteristics by region**, to align with the size, mix, and weather characteristics of 22 U.S. regions. | **BTO's Scout model** |
| 4 | **Adjust estimates to reflect achievable adoption rates and stock turnover**, based on review of regional and national EE and DR studies. | **Brattle analysis** |
| 5 | **Develop forecasts of system costs and emissions through 2030**, including generation capacity, energy, ancillary services, and transmission capacity. | **NREL's Cambium dataset** |
| 6 | **Evaluate ability of GEB measures to avoid forecasted system costs**, including dynamic dispatch of DF measures. | **Brattle's LoadFlex model** |

**FIGURE 1: METHODOLOGY OVERVIEW**

flexibility and EE program offerings. This analysis assumes that all of the analyzed technologies reach achievable levels of adoption without consideration of utility or customer cost-effectiveness. This analysis does not include the adoption of technologies through fuel switching (e.g., switching from a natural gas furnace to an electric heat pump). Additional detail on the analytical approach and key assumptions, including the adoption assumptions, is provided in Appendix B.

This study's analytical approach leveraged a combination of modeling tools, research, and analysis developed by LBNL, NREL, DOE, and The Brattle Group (see **FIGURE 1**).

## GEB Benefits

Power system benefits quantified in the analysis include avoided generation capacity costs, reduced energy costs (fuel, variable operations and maintenance (O&M), and line losses), ancillary services (i.e., fast-response services to keep the grid balanced in real-time), avoided transmission capacity costs, and avoided $CO_2$ emissions. Additional benefits that were not quantified in the analysis could significantly increase the total value estimate. Examples of additional, unquantified benefits include:

- Avoided or deferred need for distribution capacity: Geographically targeted EE and demand flexibility

## Key study features

- Leverages a suite of advanced building and market simulations tools developed by the National Labs, DOE, and The Brattle Group
- GEB performance is based on hourly building-level simulations for 43 GEB EE and demand flexibility measures and technologies across a variety of residential and commercial building types and end-uses[10]
- Includes combined EE and demand flexibility measures, accounting for interactions in their collective load impact
- Utilizes a consistent modeling framework across 22 U.S. regions, allowing for regional comparisons[11]
- Accounts for achievable technology adoption rates that are supported by market research and prior EE and demand flexibility program implementation experience
- System economic and emissions value is assessed on an hourly basis

deployments can help to alleviate the need for distribution system upgrades to meet increasing electricity demand. Benefits are highly utility- and location-specific.[13]

- Reduced need for renewable portfolio standard (RPS)-related procurement: By reducing system load, EE reduces the amount of investment in renewable generation that is otherwise required to satisfy RPS requirements.
- "Option value:" The benefits in this study are based on normal weather and load conditions. System costs are disproportionately higher when load increases due to warmer- or colder-than-average weather conditions, which would result in a higher valuation of EE and demand flexibility resources.
- Other consumer benefits: In addition to reduced costs and improved reliability, GEBs can improve the comfort, health, and productivity of building occupants,[14] increase choice and flexibility in how electricity is consumed, and reduce electricity bills.

The estimates of GEB benefits in this study would be considerably higher in a future scenario that involves significant electrification of building heating systems and transportation. The conversion of space and water heating from natural gas to electricity, as well as electric vehicle charging needs, will increase electricity demand and, accordingly, the need for supporting grid infrastructure. EE and demand flexibility could play a critical role in mitigating those investment needs and reducing the carbon footprint of buildings, facilitating the transition to a decarbonized power sector that is reliable and affordable.

## Analysis Cases

The analysis includes three main cases and three supplementary cases (see **FIGURE 2**). The main cases differ in their assumed rates of adoption of the EE and demand flexibility technologies. The supplementary cases differ in

11 See Figure 15.

12 See Figure 16.

13 See "Benchmarking Transmission and Distribution Costs Avoided by Energy Efficiency Investments," prepared by the Mendota Group for the Public Service Company of Colorado, Oct. 2014. Available at: https://mendotagroup.com/wp-content/uploads/2018/01/PSCo-Benchmarking-Avoided-TD-Costs.pdf.

14 See, for example, dynamic envelope technologies in "Grid-interactive Efficient Buildings Technical Report Series: Windows and Opaque Envelope," p. 12. Available: https://www1.eere.energy.gov/buildings/pdfs/75387.pdf.

| | CASE | DESCRIPTION | COMMON ASSUMPTIONS |
|---|---|---|---|
| Main Cases | Low Adoption | EE and DF measure adoption based on lower-end of range of achievable adoption estimates | Main cases use NREL's Standard Scenarios "Mid-Case" for marginal costs |
| | Mid Adoption | Adoption based on middle of the range of achievable adoption estimates | |
| | High Adoption | Adoption based on upper-end of range of achievable adoption estimates | |
| Supplementary Cases | Low Renewables (RE) | System cost forecast based on NREL's High Renewable Energy Cost scenario | Supplementary cases assume Mid Adoption of EE and DF |
| | High Renewables (RE) | System cost forecast based on NREL's Low Renewable Energy Cost scenario | |
| | High Capacity Value | System cost forecast based on NREL's Reference case, but modified to assume higher generation capacity value ($75/kW-yr) and to include transmission value ($30/kW-yr) | |

**FIGURE 2: ANALYSIS CASES**

**Note:** The "Low Renewables" case has lower assumed renewable generation capacity additions due to higher costs assumed for renewables technologies. The opposite applies to the "High Renewables" case.

their assumptions about renewable generation deployment and the associated impact on system costs, as well as assumptions about capacity and transmission value.[15, 16] For further details on the assumptions behind each case, please refer to Appendix B.

## National Findings

**FIGURE 3** shows annual U.S. power system impacts of EE and demand flexibility measures for each of the six cases. Depending on measure adoption levels and system conditions, between roughly half and three-quarters of total system benefits come from reduced energy costs driven largely by the energy savings of EE measures. Avoided or deferred generation and transmission capacity costs due to EE- and demand-flexibility-induced reductions in system peak demand account for the vast majority of the remaining benefits. The greatest range in the results is due to different assumptions about future technology adoption rates (i.e., Low, Mid, and High Adoption cases). The slightly lower system value of GEBs under the High Renewables case is due to lower marginal energy costs and associated reduced benefits from EE. In that case, however, more variable energy costs create greater opportunities to shift load from higher-cost hours to lower-cost hours, increasing the value of demand flexibility.

For context, currently about 10 GW of peak demand reduction capability in the U.S. is known to come from technology-enabled demand flexibility in residential and commercial buildings (see **FIGURE 4**, top panel).[17] The existing capability is concentrated primarily in residential cooling and

15 Assumptions on renewable generation deployment and system costs are from three of NREL's 2020 Standard Scenarios: the Mid Case, the High Renewable Energy Cost scenario, and the Low Renewable Energy Cost scenario. More details available at: https://www.nrel.gov/analysis/standard-scenarios.html.

16 A high electrification scenario was not modeled in the study but could identify additional GEB value. An analysis of a high electrification future would involve modeling not only changes in end-use consumption patterns (including fuel switching), but also changes in generation capacity additions due to load growth and changes in the shape of the system load profile.

17 Based on analysis of 2019 EIA-861 data, SEPA's *2019 Demand Response Market Snapshot*, and FERC's *2019 Assessment of Demand Response and Advanced Metering.* Additional technology-enabled DF may be available from buildings participating directly in wholesale markets, though data is not available at a level that allows it to be quantified.

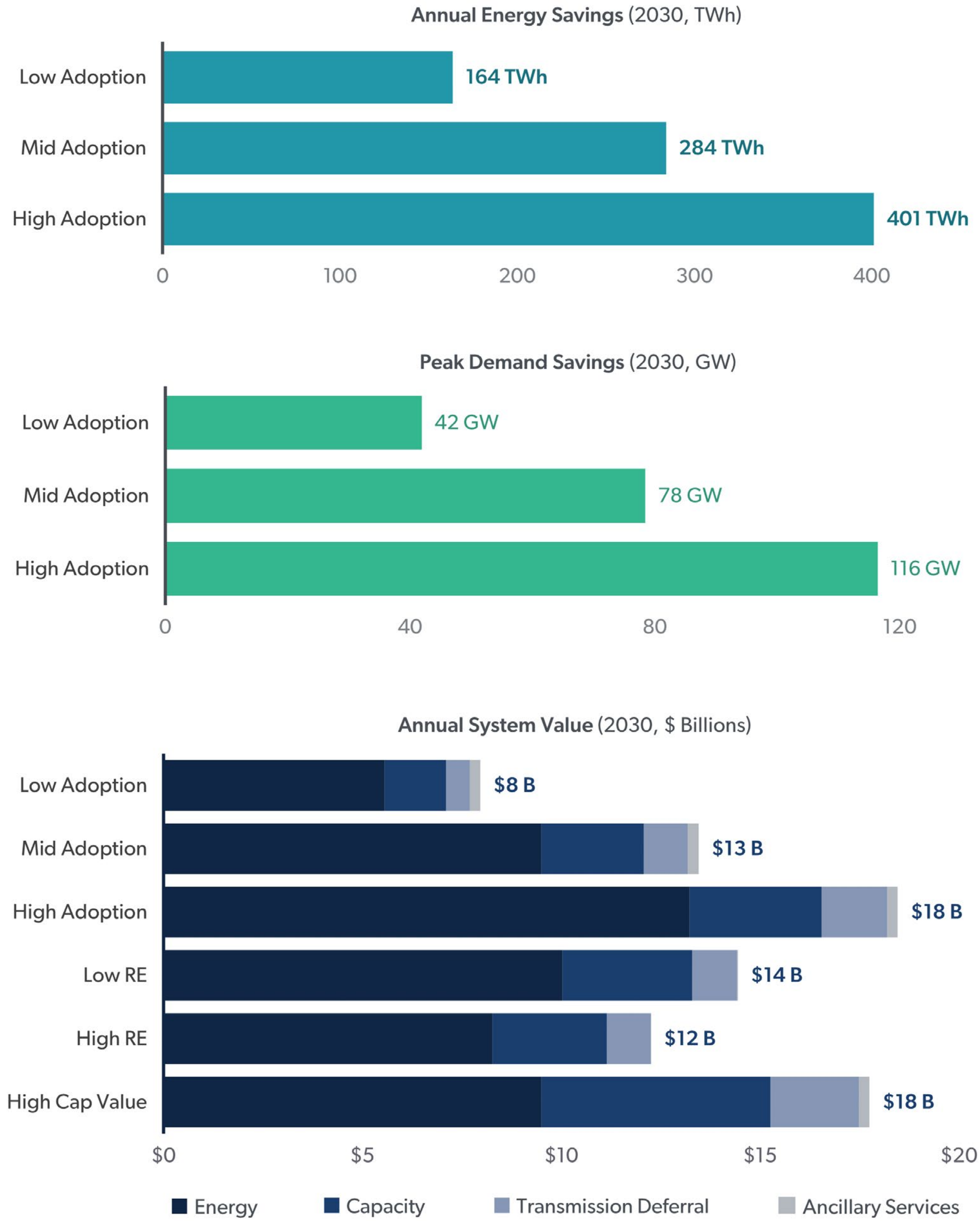



**FIGURE 3: THE U.S. POWER SYSTEM VALUE OF PEAK DEMAND AND ENERGY SAVINGS DUE TO ACHIEVABLE LEVELS OF GEB ADOPTION**

**Notes:** All in 2019 dollars. Peak demand savings are computed as the sum of impacts during each region's coincident peak hour. Note that Low RE, High RE, and High Cap Value have the same energy and peak demand savings as the Mid Adoption case.

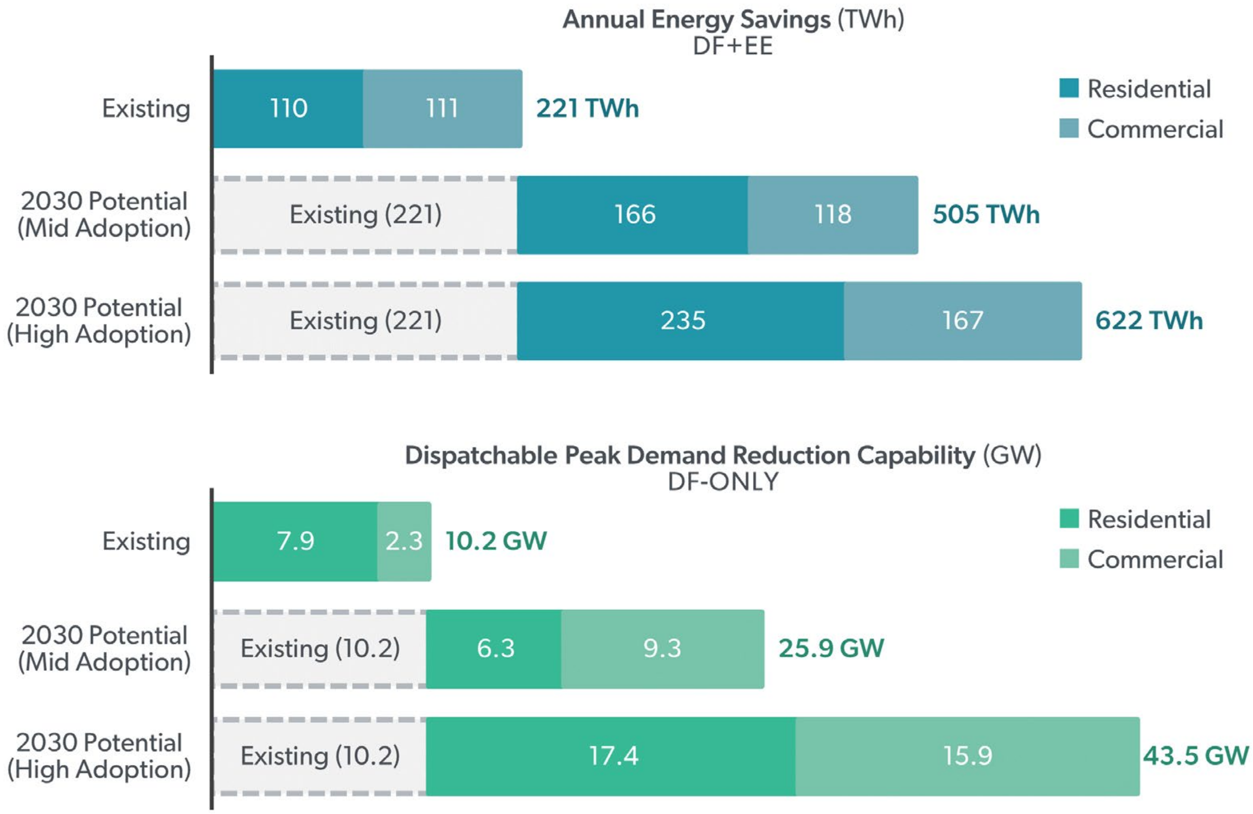



**FIGURE 4: PUTTING THE GEB POTENTIAL ESTIMATES INTO HISTORICAL CONTEXT**

**Notes:** 2030 peak reduction capability estimates are for a case with only demand flexibility deployment (i.e., no EE). Peak demand reductions are computed as the sum of impacts during each region's coincident peak hour. 2030 annual energy savings are for the DF+EE cases described in Figure 2, in which both DF and EE measures are adopted. "Existing" covers EE capability developed between 2010 and 2019. "2030 Potential" covers modeled savings capability that could be developed between 2021 and 2030 and is incremental to existing EE.

water heating direct load control. As shown in **FIGURE 4**, this study has identified 15.6 GW (or about 1.5 times the existing capability) of new, dispatchable peak-reduction capability from demand-flexibility-only programs coming online by 2030, with 6.3 GW provided by residential GEBs and 9.3 GW by commercial GEBs.[18] This new peak-reduction capability is additive to existing capability, so total peak-reduction capability could reach 25.9 GW by 2030. Under plausible but more aggressive GEB-adoption assumptions, new peak-reduction potential from GEBs could reach 33.3 GW by 2030, or 3.3 times existing capability, and could contribute to a total peak-reduction capability of 43.5 GW (see High Adoption case in **FIGURE 4**).

Similarly, the energy savings potential of GEBs identified in this study is higher than recent EE program savings levels (see **FIGURE 4**, bottom panel). The estimates in this study are based on voluntary (i.e., opt-in) technology adoption rates, so they are compared to historical trends in residential and commercial utility EE programs with similar voluntary participation. Utility programs implemented during the past 10 years (i.e., between 2010 and 2019) reached accumulated energy savings levels of 221 TWh/yr by the end of 2019, as shown in **FIGURE 4**.[19]

18 The DF-only case assumes only DF programs are adopted; no EE programs are adopted. This case has higher ***dispatchable*** peak reduction potential than that of the Mid Adoption case (in which both EE and DF measures are adopted), because EE programs reduce the DF capability in the Mid Adoption case. Note that total (dispatchable and non-dispatchable) peak demand reduction from the Mid Adoption case is higher – 78 GW – than the DF-only case as shown in Figure 3.

19 Based on analysis of historical annual incremental savings presented in EIA-861 data.

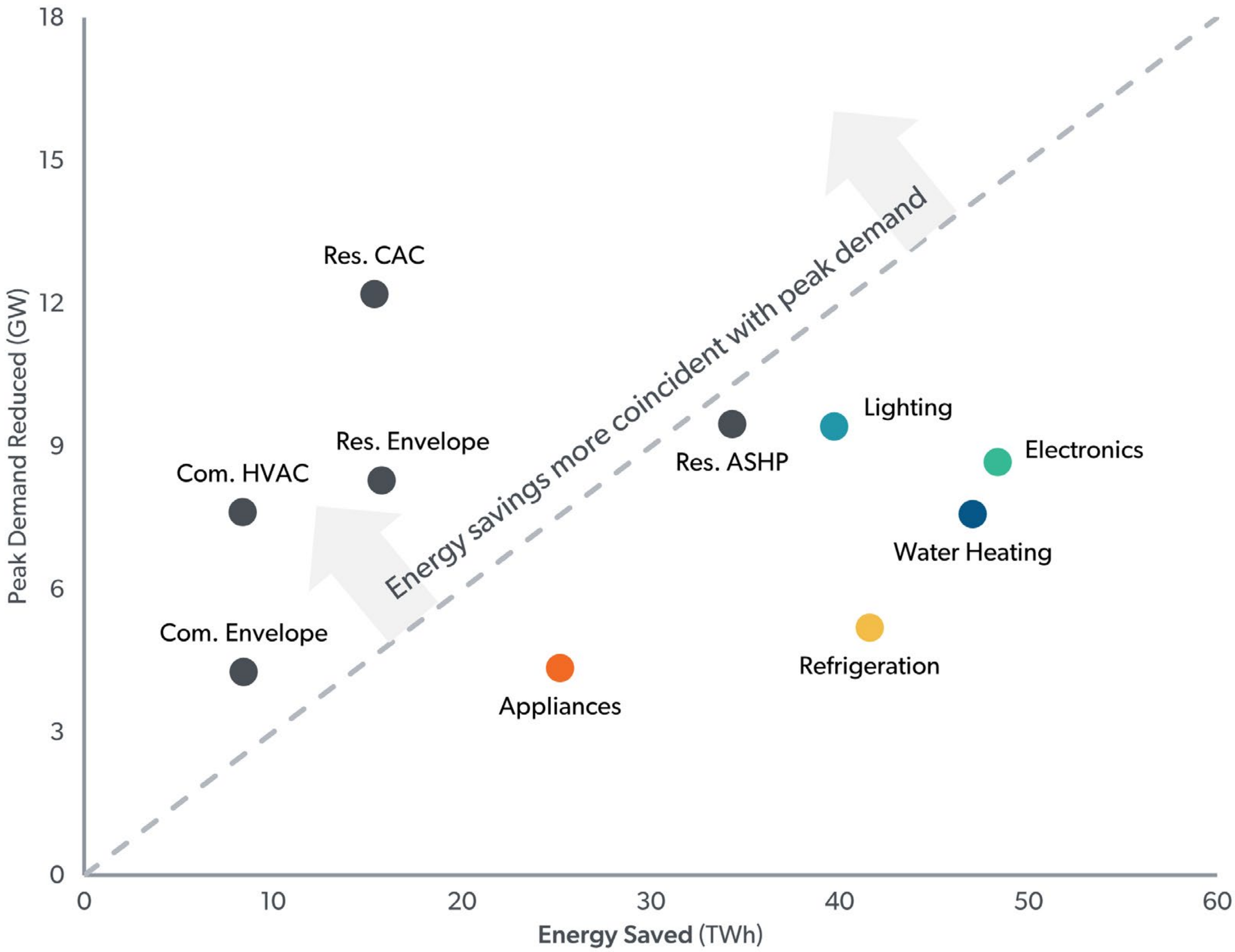



**FIGURE 5: ENERGY AND PEAK DEMAND SAVINGS BY MEASURE TYPE (2030)**

**Notes:** Values shown correspond to the Mid Adoption case. Regional detail is provided in Appendix B. "CAC" is central air-conditioning. Water heating impacts are primarily driven by heat pump adoption. Each type of measure has some element of demand flexibility, except for refrigeration, which was modeled strictly as providing EE benefits. Measure types are defined in Figure 15. The Residential Preconditioning measure results are excluded as they do not map exclusively to CAC, ASHP, or Envelope.

In comparison, the GEBs adopted over the next 10 years could provide energy savings of 284 TWh/yr by 2030 (166 TWh/yr residential, 118 TWh/yr commercial). The energy savings from newly adopted GEB measures are additive to existing savings, so total energy savings could reach 505 TWh/yr by 2030. Assuming more aggressive adoption rates, total annual energy savings could reach 622 TWh/yr by 2030, with new GEB measures providing 402 TWh/yr of savings and existing programs providing 221 TWh/yr of savings (see High Adoption case in **FIGURE 4**).

This analysis has directly informed DOE's national goal for GEBs: To triple the energy efficiency and demand flexibility of the buildings sector by 2030 relative to 2020 levels.

## Findings by Measure Type

The measures analyzed in this study make varying contributions to the total EE and demand flexibility impact estimates due to differences in the magnitude and hourly shape of the impact profiles of each EE and demand flexibility measure, as well as differences in adoption rates (see

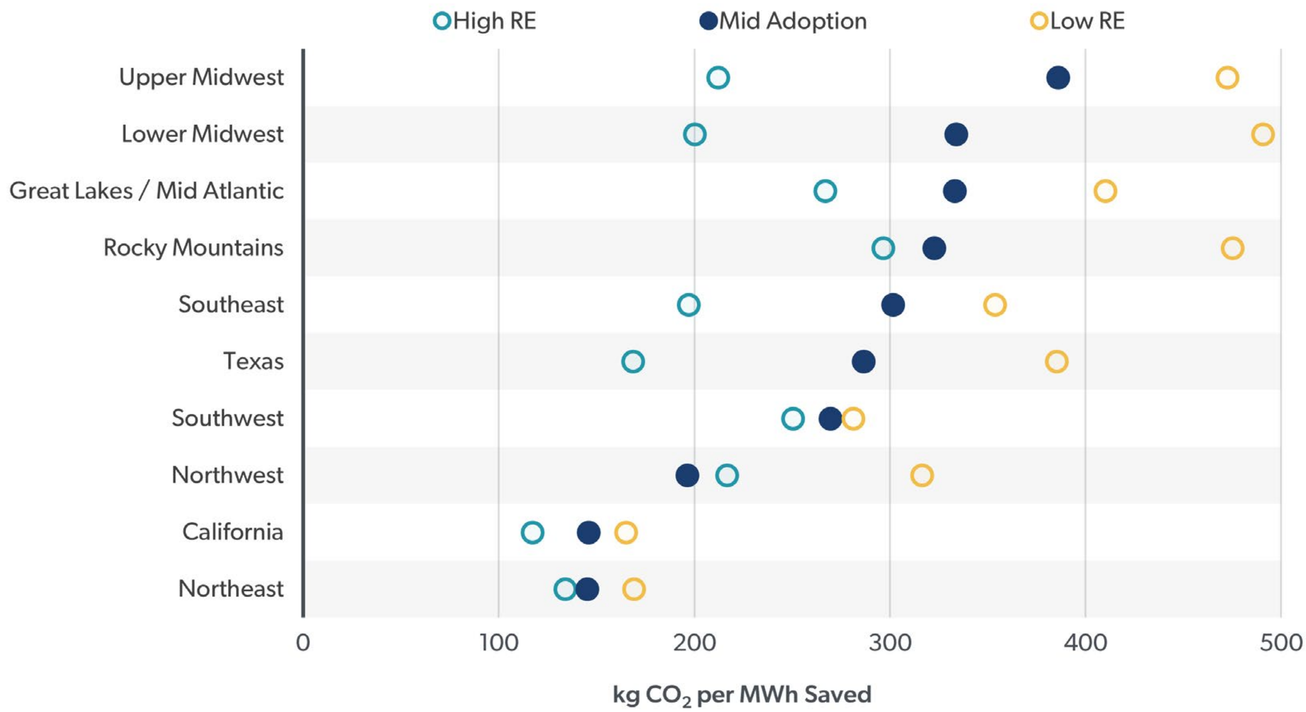



**FIGURE 6: $CO_2$ EMISSIONS REDUCTION PER MWH OF ENERGY SAVINGS FROM GEBs (2030)**

Appendix B for modeling details). **FIGURE 5** summarizes the energy and peak demand savings for each major group of residential and commercial measures considered in the study. Collectively, HVAC and envelope EE and demand flexibility measures are the single largest driver of the impact estimates and provide the largest aggregate energy and peak demand savings of all analyzed end uses. EE and demand flexibility savings from HVAC and envelope measures also tend to occur at the time of system net peak demand, indicating that the energy saved by those measures is more valuable to the power system on a per-MWh basis than measures with a higher concentration of savings during off-peak hours.

The water heating, refrigeration, electronics, appliances, and lighting measures analyzed in this study have lower peak demand-to-energy savings ratios than the HVAC and envelope measures. This is consistent with the measures' usage patterns being less peak-coincident, and generally having a flatter usage profile across the hours of the day and across seasons. The addition of supplemental thermal storage could improve the peak-reduction potential of water heating and refrigeration.[20]

## Emissions Impacts

By 2030, the GEB measures analyzed in this study would reduce national $CO_2$ emissions by roughly 80 million tons in the Mid Adoption case, or 6% of total power sector $CO_2$ emissions in that year.[21] The primary driver of the emissions reductions is the decrease in fossil fuel-based electricity generation due to lower overall electricity demand. Additionally, changes in the timing of electricity consumption through demand flexibility measures and technologies can shift usage to hours with lower emissions rates (e.g., middle-of-the-day in a utility system with high solar deployment).

20 The U.S. DOE Building Technologies Office has published a series of technical reports discussing detailed considerations for a wide variety of GEB technologies. For further information, see the Technical Reports listed here: https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings.

21 While this study only quantifies $CO_2$ reductions, EE and DF also support reduction of criteria pollutant emissions.

The rate of $CO_2$ emissions avoidance varies significantly across regions and renewables deployment scenarios (see **FIGURE 6**).[22] Regional differences in emissions rates are attributable to differences in the existing supply mix, as well as future capacity additions and retirements. Regions that are more reliant on carbon-intensive generation resources (e.g., the upper Midwest), or that do not have plans to serve new load through cleaner resources, will provide a greater opportunity for $CO_2$ emissions reductions through EE and demand flexibility. Relatedly, those regions tend to demonstrate the broadest range of possible emissions benefits across the renewable energy deployment cases. In contrast, regions with a cleaner supply mix tend to be more likely to add clean generation resources in the future, regardless of the renewables deployment scenario, resulting in a lower and less variable $CO_2$ reduction opportunity (e.g., California and the Northeast).

22 Results presented at the EPA AVERT geographic level, as shown in Figure 28. LoadFlex modeling was performed at the more granular EIA EMM geographic level, as shown in Figure 16.

# 3. The GEB Vision and Technology Integration

## Introduction

This chapter describes a vision for GEBs, with a review of the key technologies needed and how they could be integrated to realize the vision. Achieving the GEB vision is critical to realizing the benefits to the electric power system described in Chapter 2. A key element of this vision is to take full advantage of diverse building loads by enabling a building to have multiple end uses that can provide grid services and an important next phase of BTO's GEB research and analysis will focus on the integration of DERs. Through increased controllability of end uses and flexible electricity consumption, customers can benefit from lower electricity bills, improved electricity reliability, and greater comfort and productivity. While EE and demand flexibility can be realized through individual end-use technologies, a fully optimized GEB uses advanced controls for active and continuous energy management of EE and demand flexibility across building systems.

## Evolution of EE and Demand Flexibility

To take advantage of GEB features, energy programs must evolve to simultaneously promote load flexibility and smart energy management (see **FIGURE 7**). Though they will improve the ability to control building equipment for optimal EE, many current advances in smart energy management may have minimal impact on demand flexibility. Similarly, although automated demand response (ADR) programs promote demand flexibility by enabling automated load shedding and load shifting through financial incentives and rebates, they provide minimal improvement in EE.

Integrated demand-side management (IDSM) programs represent an improvement over these simpler programs by combining retrofits to support both EE and DR goals, thus enabling customers to benefit from the combined value of integrated control upgrades. For example, utilities have historically targeted electric resistance water heaters to provide grid services, but a more efficient grid-interactive heat pump water heater (HPWH) demonstrates the capability of this end-use load to be met with energy-efficient technology that provides grid services. Likewise, improving insulation, reducing infiltration, and retrofitting single-paned windows with high-performance double or triple glazed windows will reduce the size of the HVAC system needed for heating and cooling, as well as reduce the building peak demand. These improvements to tighten the building envelope will improve the use of HVAC as a flexible load because thermal energy to heat and cool the building can be stored in the building mass.

Other IDSM DER aggregation pilots are a step towards

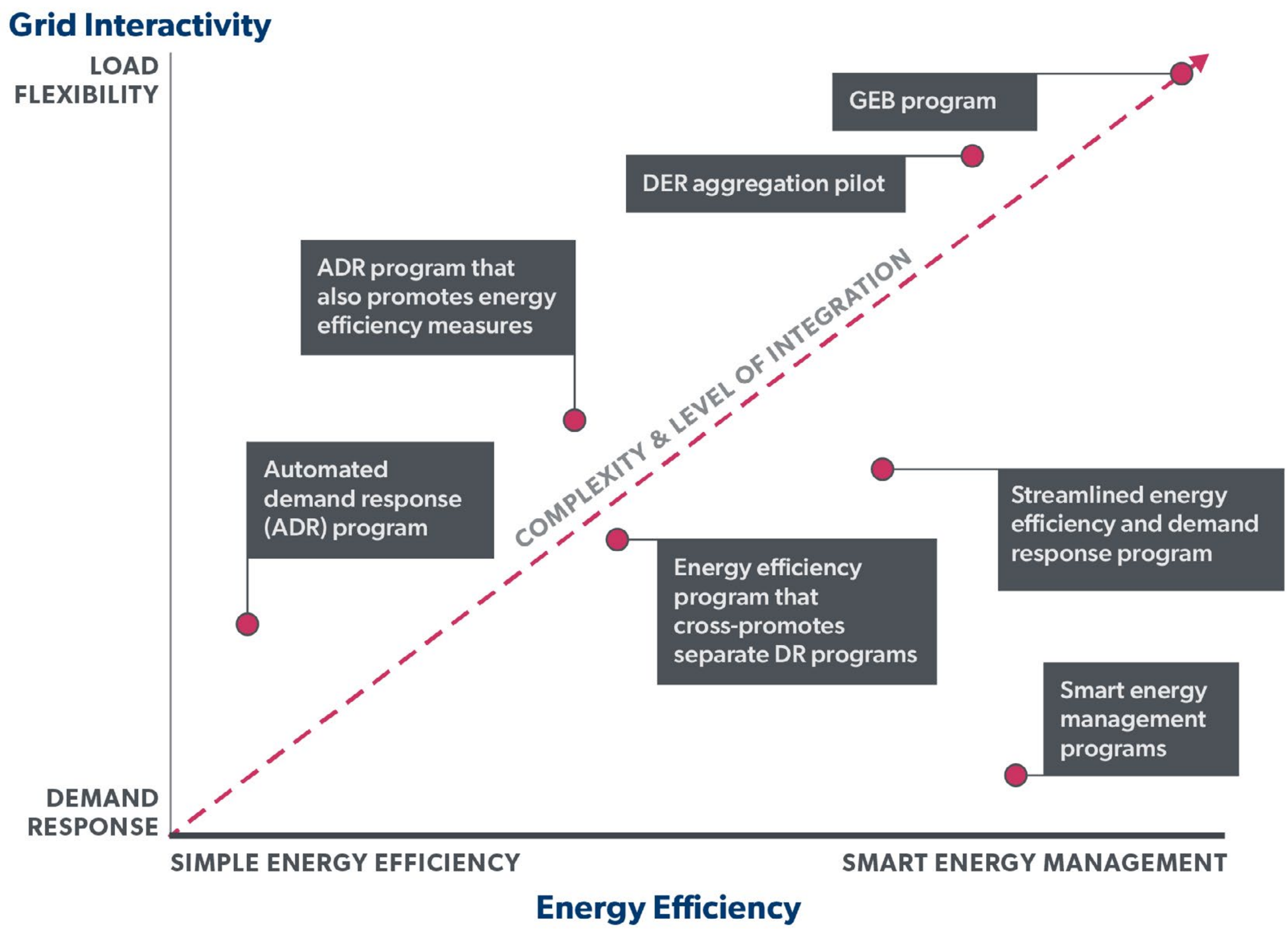



**FIGURE 7:** EVOLUTION OF GEBS WITH INCREASING LOAD FLEXIBILITY AND SMART ENERGY MANAGEMENT

**Source:** Adapted from *the American Council for an Energy-Efficient Economy (ACEEE, 2019).*

the future of programs that combine EE and demand flexibility features. These programs combine loads across numerous buildings to provide grid services and may also integrate PV, electric battery storage, and other DERs. Future advancements in building technologies and energy programs are needed to realize the vision of making buildings both energy efficient and grid interactive (see **FIGURE 7**).

## The GEB Vision: Dynamic, Smart, and Integrated Building Systems

The GEB vision describes the features of a whole-building integrated approach and can be used to identify the innovations needed to move beyond individual technologies. **A GEB is capable of providing energy-efficient building services and dynamic grid services through connected, smart control of multiple flexible building loads and DERs**. We provide the following description of these attributes.

1. **Efficient:** GEBs can provide similar or improved energy-efficient building services relative to the existing level of service provided. The services may include meeting the basic needs of occupants – such as thermal and visual comfort, indoor air quality, and hot water. Important building services also include numerous functions such as vertical transport (i.e., elevators), refrigeration, cooking, clothes washing and dishwashing, entertainment, computing, and printing.

2. **Connected:** GEBs enable two-way communication between technologies, the grid, and occupants for

responding to time-dependent grid needs.

3. **Smart:** GEBs support advanced control for buildings and community energy systems and are characterized by several capabilities, including the ability to:

   - Co-optimize multiple end-uses and DERs, including generation and storage.
   - Optimize operations over a time window and incorporate predictions about relevant inputs into the optimization (e.g., weather, occupancy, renewable energy generation, and grid needs). This capability is necessary to leverage storage and other sources of scheduling flexibility to proactively shape energy use over multiple time scales in order to effectively respond to grid needs while minimizing negative impacts on occupants.
   - Optimize for multiple objectives (e.g., overall energy use, energy use during specific times, occupant comfort).
   - Adapt various aspects of control over time to reflect changes in building assets and usage, weather, and objectives.

   To provide these capabilities, instead of relying on fixed rules, GEB control systems rely on advanced implementation techniques like modeling, optimization, allocating resources according to prices, and machine learning.

4. **Flexible:** GEBs can provide dynamic load control to support the electric grid, including shedding, shifting, and modulating loads. Modulating loads provide ancillary services (e.g., frequency regulation) and voltage control. One important attribute of grid services from buildings is how fast the load can respond to an automated signal. In general, fast responding controls, communications, and loads can provide a broader set of grid services.

## GEB Technology Integration Layers

Several DOE GEB Technical Reports identified high-priority emerging building technologies based on their potential to provide grid services, as well as identifying technology-specific challenges and R&D opportunities.[23] These reports focused on technologies that provide building services and did not cover the broad capabilities of DERs and integration with GEBs, which is discussed at the end of Chapter 3. Based on the technology evaluations in the three end-use specific reports, the high demand flexibility potential GEB technologies were classified into three distinct groups based on their ability to provide grid services and current market status (see **TABLE 3**). The market status is a measure of how ready the concept is for commercial deployment. **FIGURE 9** extends this concept and describes the overall technology development pipeline for GEB technologies.

Most of the technologies identified in **TABLE 3**, which covers hardware, equipment, and packaged materials associated with the building structure, can be categorized as physical end uses, appliances, or structural systems. Significant changes in electric load can be achieved with these systems, such as adding thermal energy storage to an HVAC system. However, integrating building technologies, including envelope technologies, is key to activate the full GEB potential of building systems with minimal impact on building services or EE. For example, upgrades to or integration of HVAC and lighting sensing and control can provide new capabilities to manage hourly loads, providing information such as occupancy, zone temperature distributions, air flow, and other parameters. Similarly, an advanced GEB, or one consistent with our vision utilizing best practices for both efficiency and grid interactivity, should have robust features such as a well-insulated façade and dynamic envelope, solar and daylighting control integrated with HVAC, and lighting control for optimal load flexibility. Controlling solar gain and reducing infiltration can help

23 The DOE reports address general research gaps and challenges, as well as (1) whole-building controls, sensors, modeling, and analytics, (2) windows and opaque envelope, (3) HVAC, water heating, appliances, and refrigeration, and (4) lighting and electronics. Complete citations and links to each report can be found in the References section of the ***Roadmap*** under the heading "Relevant DOE Publications."

| MARKET STATUS | GEB TECHNOLOGIES WITH HIGH DF POTENTIAL | R&D CHALLENGES |
|---|---|---|
| **Commercially Available** | • Smart thermostats<br>• Water heaters with smart connected controls<br>• Automated window shading attachments | • Limited interoperability with other smart building systems and utility control systems<br>• Aesthetic concerns of certain high DF potential GEB technologies hinder adoption |
| **Pilots & Limited Availability** | • Dynamic glazing<br>• Continuous operation electronics<br>• Advanced sensors and controls for lighting<br>• Separate sensible and latent space conditioning<br>• Non-vapor compression materials<br>• HVAC integrated and add-on module thermal storage | • Limited control capabilities for responding to grid signals and balancing response with user preferences<br>• High first costs for stand-alone grid-interactive products as well as for adding GEB capabilities to existing products (e.g., sensors and controls for lighting)<br>• Complexity of installation and maintenance |
| **In Development** | • Thermally anisotropic materials<br>• Tunable thermal conductivity materials<br>• Liquid desiccant thermal storage<br>• Advanced thermal storage materials and composites | • Limited and new R&D showing promise to introduce these new thermal technologies over time |

**TABLE 3: PROMISING GEB TECHNOLOGIES BASED ON COMMERCIAL AVAILABILITY**

**Note:** Not all challenges listed in Table 3 are applicable to each technology. For example, aesthetics concerns are a specific challenge hindering the adoption of automated window shading attachments but not necessarily the other technologies in that category.

minimize cooling loads. Finally, strategies like pre-cooling to shift air conditioning use to earlier in the day can be done with minimal impact on occupant comfort.

**FIGURE 8** depicts the functional attributes that can be integrated with building end-use and envelope systems, as well as DERs, to realize the full opportunities of GEBs. The bottom of the figure shows the services the building provides occupants, including shelter, comfort, hot water, refrigeration, and light. These services are provided by physical end-use systems such as the building envelope and structure, HVAC, appliances, lights, and other equipment. The next layer up includes sensors and actuators that are needed for dynamic control of these systems. Fully integrated GEBs may provide more sensing than traditional buildings, with measurements of temperature, occupancy, light levels, hot water, and other key attributes that are used to evaluate the load flexibility. The next two layers above show local and supervisory control, and the top level of the graphic shows the building to grid interface. Integration of DERs with the building can occur at either the supervisory or local control layer. For example an EV charger may integrate a single EV, but a supervisory control system may integrate building loads and DERs to minimize total costs for a homeowner.

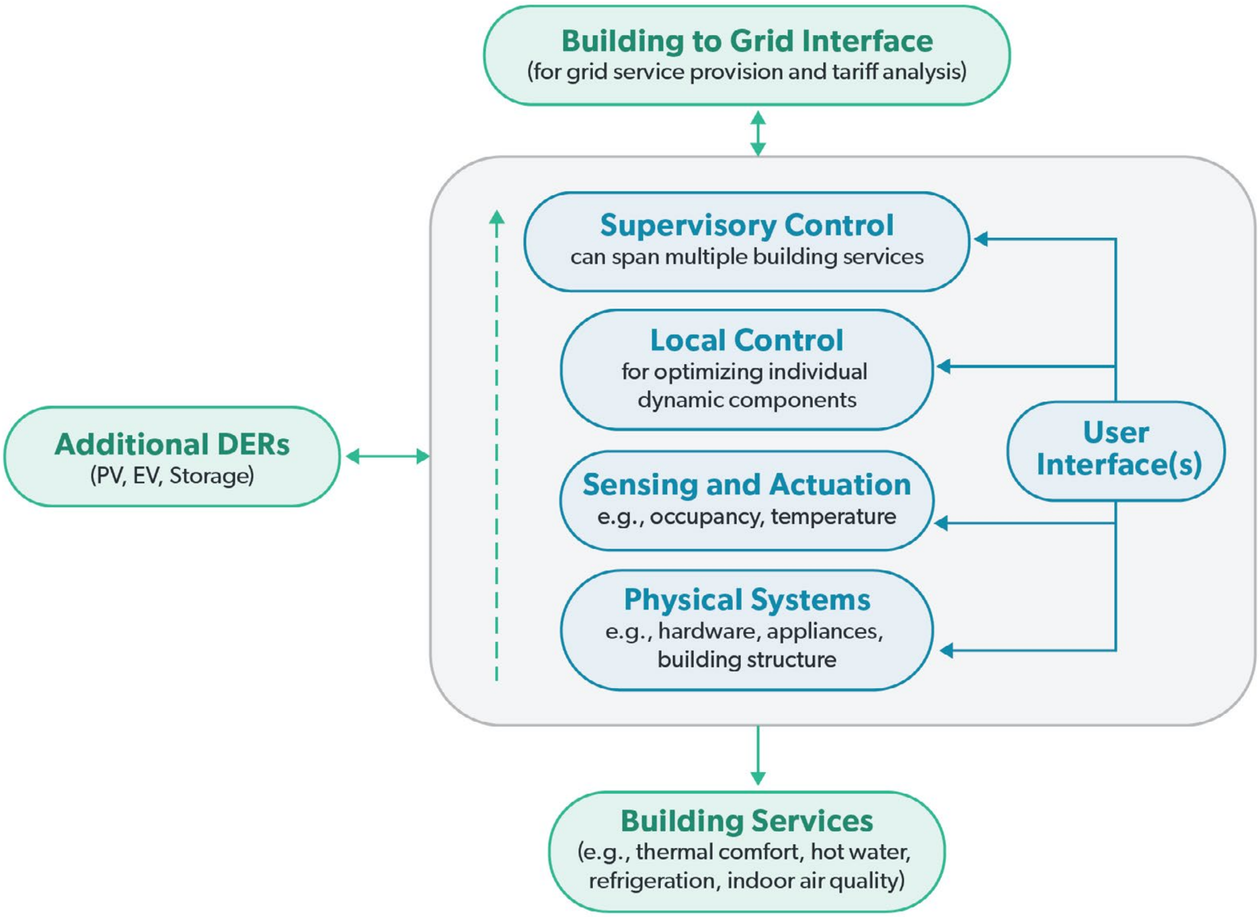



**FIGURE 8:** GEB TECHNOLOGY LAYERS

This graphic is useful when thinking about the interaction between and the integration across different GEB technology layers. For example, many smart thermostats have the capability to provide building-to-grid communication. Similarly, some water heaters use a CTA-2045 communication module to communicate with the grid. Each layer could either be embodied in an individual technology and then functionally integrated (e.g., HVAC connected with a thermostat), or they could be physically combined into a single technology (e.g., a basic water heater with a CTA-2045 port combines the hardware and sensing layers).

Two types of technology integration are important from a GEB perspective (see Figure 8). First is the integration ***between layers***, which is important to maximize the performance of each end-use and avoid conflicts between competing objectives. Second is the integration ***across multiple end-uses*** at the supervisory control layer to take advantage of synergies between end-use systems, including DERs, and achieve further optimization of building operation. As mentioned, grid communication can occur from either local or supervisory control systems. If multiple end-uses or DERs are communicating with the grid, the use of supervisory control is needed to ensure the systems are coordinated and integrated. Figure 8 also shows that the integration of PV, electric vehicles, energy storage, and other DERs which can be provided by capabilities in evolving residential Smart Home Energy Management Systems (SHEMS), commercial Building Automation Systems (BAS), and techniques like model predictive control. This integration might also be coordinated by an aggregator or third-party service. Finally, the figure also shows the user interface with the GEB, which can take place in many forms – such as a display on a wall, computer, or smartphone interface. Appendix E describes

## Smart Home Energy Management System and BASs

Our definition of a SHEMS is a supervisory control system that can integrate more than one end-use or DER. This GEB technology area is challenging due to the lack of interoperability across end uses. While there are many products and methods to communicate with a single device in a home, like an air conditioner or a water heater, there are fewer systems on the market to integrate end-use systems as well as DERs. This technology is somewhat more developed for large commercial buildings with integration gateways. Although some BAS may be integrated with lighting controls and other DERs, most BASs only control HVAC. Additionally, some BAS and lighting control systems can receive grid signals with the installation of an OpenADR gateway. In other cases, the BAS or lighting control system may have grid communication capabilities such as OpenADR available as a native element of the control system.

the functional layers and integration options in more detail.

Interoperability, which is the ability of devices or software systems to reliably exchange information, is necessary for enabling "plug and play" operation of GEB technologies and for the flow of information across integrated layers. Interoperability includes using data from sensing and communication in individual end uses and allowing for integrated control. This behavior also requires semantic interoperability, which is the use of shared vocabulary and a common understanding of the meaning of the exchanged data. Semantic interoperability is necessary for data to be interpreted by various integrated GEB systems. Promoting widespread implementation of interoperability in GEB technologies will help reduce the cost of GEBs, avoid stranded assets, allow greater market innovation, and help ensure that devices from different manufacturers and control companies can be integrated. As with interoperability, cybersecurity must be implemented at multiple layers in GEBs, from individual devices to systems, whole buildings, service aggregators, and the grid.[24] Appendix E provides additional discussion on interoperability and grid communication standards.

Various building types have unique constraints for adapting the GEB technology layers (see Figure 8). Certain layers have features that can be commonly utilized, while other layers may have features customized for a building type, including residential homes, small commercial buildings, and large commercial buildings. **TABLE 4** summarizes examples of idealized GEB technology features for each building type. While not an exhaustive list of all possible features, the examples describe key features in hardware and software not commonly found in buildings today that would provide efficient building services, can be integrated with additional DERs (e.g., solar PV, electric storage, EVs), and that enable greater load flexibility to provide grid services.

Many of the technologies in Table 4 are commercially available in some form, but are highly custom systems and are therefore expensive with limited market adoption. Figure 9 identifies several key GEB technologies under development that vary in terms of their commercial readiness, categorized as commercially available, pilots & limited availability, and in development. All of these technologies need to be deployed at a far greater scale to enable the capabilities of GEBs. The key technologies were identified through the GEB Technical Reports and expert elicitation (see Appendix E for more detail on key GEB technology selection).

24 For more details on cybersecurity for buildings, please refer to Reeve, et al. (2020). Available at: https://www.energy.gov/sites/prod/files/2020/05/f74/bto-pnnl-29813-securing-buildings-cyber-threats-051420.pdf.

| GEB Integration Layers | Residential | Small Commercial | Large Commercial |
|---|---|---|---|
| **Physical Systems, Hardware, and Equipment** | Insulated and tight envelope, persistent and flexible high-power loads, e.g., space conditioning, water-heating | | Insulated and tight envelope, Persistent and flexible loads, dynamic façade, HVAC, lighting, MELS[1] |
| **Sensing** (temperature, air flow, energy use, occupancy, light level) | Granular sensing for predictable and reliable service delivery | Granular, distributed sensing for predictable and reliable building and grid service delivery | Granular, distributed sensing for predictable and reliable building and grid service delivery, state of charge sensing for active or passive thermal storage |
| **Local Communication and Control** | End-use controls, such as thermostats or HPWH, capable of interacting with supervisory control and adjusting set points based on external input | | |
| **Supervisory Communication and Control** | SHEMS[2] providing predictive integrated control | SHEMS-like system providing predictive integrated control | BAS and other EMIS[3] providing predictive integrated control |

**TABLE 4: KEY FEATURES FOR ENABLING GEB TECHNOLOGY INTEGRATION IN EACH BUILDING TYPE**

**Acronyms:**
**1)** Miscellaneous electric load (MELs), **2)** Smart Home Energy Management System (SHEMS), **3)** Energy Management Information System (EMIS).

The key GEB technologies are grouped according to their GEB technology layer (see layers in **FIGURE 8** and **FIGURE 9**) to illustrate how technologies for an integrated GEB may exist in various stages of development. Thermal Energy Storage (TES) is assigned its own category as a subset of physical systems because of its unique demand flexibility potential. At the physical layer, certain end-use equipment and envelope system technologies have high demand flexibility potential when paired with control technologies, as well as high-efficiency improvement potential through electrification (e.g., heat pumps, HVAC and hot water combination systems, heat pump water heaters), or the systems improve the demand flexibility potential of HVAC end uses (e.g., automated window attachments, dynamic glazing).

Technologies at the local control level are represented by specific physical systems with controls (e.g., water heaters, connected lighting, appliances, and MELs) as well as controls technologies that work with building systems to enable grid-interactive behavior (e.g., smart thermostats with a connected HVAC system). All of the local controls and supervisory control technologies at the top of the graphic are "DF-Enabled," which denotes the addition of demand flexibility capabilities to automatically respond to grid signals and provide grid services. The supervisory control layer illustrates technologies that can coordinate grid-responsive behavior across multiple end uses (e.g., SHEMS, BAS), across multiple buildings (e.g., multi-building control), or improve the control capabilities of existing supervisory control systems (e.g., predictive control).

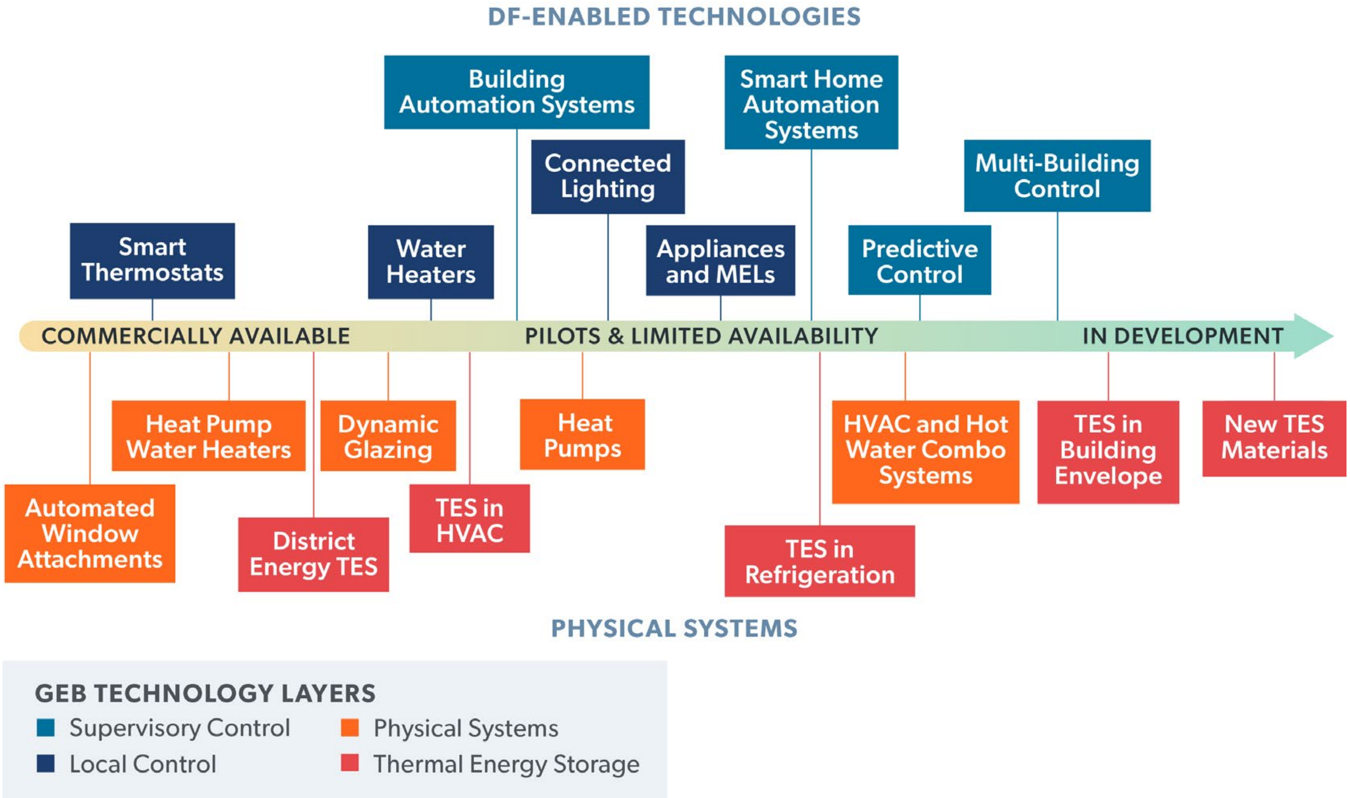



**FIGURE 9: TECHNOLOGY PIPELINE EXAMPLES FOR EACH GEB LAYER**

**Note:** TES integrated with HVAC is available in large commercial buildings but rare in small commercial or residential buildings.

The new building technologies in development will revolutionize how we heat, cool, and control our homes and buildings, facilitating optimal EE with affordable, seamless load control. Close attention to and investment in these emerging technologies will ensure that we can accelerate the pipeline and develop advanced, affordable, and desirable GEBs in the coming decade.

# Enhancing GEBs through Integrating Distributed Energy Resources

The GEB Technology Reports Summary (Appendix E) and Technology Pipeline (**FIGURE 9**) discussed above primarily focus on opportunities for improving the efficiency and flexibility of building loads from building equipment systems. Looking to emerging trends, the integration of DERs with building loads will become a critical element of the GEB vision. This summary highlights opportunities and challenges that will need to be addressed for integration and optimization with buildings loads at scale, and lays out the foundation for future analyses.

## The Emerging Opportunity

The additional benefits of coordinated deployment of building-integrated DERs will improve the GEB value proposition. New building loads – such as electric vehicle (EV) charging – are projected to become a significant source of demand and demand flexibility that can be synergistically coordinated with building loads to provide additional grid interactivity. Energy storage systems provide a variety of valuable GEB use cases, including for resilience (as a form of on-site backup generation), for firming PV generation when paired as a hybrid resource, and for providing capacity and ancillary services value to utilities and system operators. PV has grown rapidly as a means to reduce building demand and provide clean energy back to the grid; building-integrated PV can be coordinated to reduce thermal envelope and lighting loads. And, GEBs can support the utilization of PV in cases where managed consumption of building loads serves as a storage resource. Integrating DERs with buildings will promote aggressive carbon savings by supporting higher levels of variable renewable energy. Other DERs should also be considered, including geothermal, hydrogen fuel cells, and low-carbon combined heat and power (CHP).

While still relatively modest in size today, building-integrated DERs could greatly increase the future value of GEBs. For instance, the number of EVs nationally could reach 65 million (light-duty vehicles) in 2028 with widespread managed charging. And, solar PV deployment is projected to increase 2-to-5 times 2020 levels.

## Research Needs for Increased Integration of DERs in GEBs

As will be discussed in Chapter 5 of the Roadmap, there are actions that can be taken by all stakeholders to address energy efficiency and demand flexibility deployment barriers that are relevant to traditional building loads, as well as emerging building loads from the DERs discussed in this section. As the GEB vision expands, there are additional opportunities to explore greater integration of DERs highlighted below.

Several cross-cutting research ideas are germane to the integration of DERs in GEBs. These include:

- Improved tools that quantify the market potential and communicate the value proposition of GEB-DER integration to designers, construction firms, building owners, and customers.
- The collection of data for building load forecasts and operational optimization, and the validation of continual benefits and durability of technologies.
- How to cost-effectively upgrade existing buildings with technologies (both existing and emerging) that are grid-interactive and include advanced diagnostics and integrate DER controls.
- Opportunities for workforce education and training to close knowledge gaps regarding how to best integrate DERs with demand flexibility.
- Exploring the pros and cons of integrated DERs at individual buildings versus larger-scale DERs (e.g. community solar) where building loads are integrated as part of a community scale-controlled system.

In addition, there are near-term research needs specific to each DER. A next step in U.S. DOE's GEB research will be identifying high-impact opportunities. A few highlights include:

- Pursuing research related to building-integrated PV focused on optimizing the solar PV production with building loads, integrated design with rooftops, windows, and facades, and field demonstrations of DC buses and power sources in buildings.
- System level integration of battery storage thermal management systems with building thermal loads.
- Exploring the integration of EVs with other building loads, which requires measures such as developing algorithms for when to charge and discharge to achieve optimal and reliable EV performance relative to other building loads and grid needs; researching the costs and benefits of newly increased building electric load to the building and any required electric panel and connection upgrades; and accurately forecasting EV load usage across users and building types.

## Overview of Key DER Deployment Challenges

Despite deployment progress, challenges remain to be addressed to meet the opportunity that DERs can provide. Many of these challenges represent an extension of those of EE and demand flexibility (see Chapter 4), but with some nuanced differences. These challenges are organized into six categories and summarized below.

1. **Customer and market value proposition:** High up-front cost and unfamiliarity with maintenance requirements remain a major deterrent to DER adoption. This is particularly true in the case of energy storage and EVs which, despite rapid cost declines, currently are more expensive than alternative options. Further, some consumers may be hesitant to allow even limited control of these technologies.
2. **Technology maturity:** Some DER technologies are rapidly changing, which can limit DER deployment. For example, EV charger technology is continuing to innovate, introducing a potential risk to early adopters of technological obsolescence. Another example is in regulatory treatment of energy storage devices by state utility commissions.
3. **Industry acceptance:** The building design and construction industry lacks familiarity with relevant technologies, as well as access to technology performance data and design tools. For example, in the case of rooftop-integrated solar PV, there is limited collaboration across the solar and roofing industries, and for building-integrated PV, there are gaps in industry participants' ability to account for factors affecting technology performance (e.g., shading) in more complex built environments.
4. **Consumer acceptance:** Due to lack of familiarity with emerging technologies, consumers may perceive risks that are greater than reality. For example, range anxiety by EV owners may limit participation in EV managed charging programs, even if safeguards in the program design mitigate risks of depleting the EV's battery when needed.
5. **Interoperability and cybersecurity:** Interoperability between DER communications, control protocols, and building systems is lacking. Cybersecurity concerns exist where grid reliability depends on the operation of DERs that are managed over potentially fragmented and insecure networks.
6. **Permitting and codes:** Inconsistent regulations for permitting PV and energy storage systems across jurisdictions increase project costs and complexity. Also, DERs which add new building loads, like EVs, may require utility service panel upgrades and conflict with building codes that have a performance standard based on reductions in electricity consumption relative to baseline.

# 4. Barriers to GEB Adoption and Deployment

## Introduction

Despite the significant potential for utility and consumer benefits through increased GEB deployment, a number of barriers and challenges must be addressed. While barriers to traditional EE have been studied extensively, less emphasis has been placed on barriers to demand flexibility, as this is still an emerging area of interest.[25] This chapter summarizes the top barriers to GEB adoption and deployment. Many of those barriers are common to both EE and demand flexibility, but barriers unique to demand flexibility are also identified.

The *Roadmap's* authors identified and prioritized the barriers, informed in part by the following activities:

- **Literature review:**[26] Reviewed more than 30 reports on EE and demand flexibility barriers, with a focus on those published in the past five years. The reports reflect a variety of perspectives, including those of DOE, National Labs, other research organizations and consulting firms, and policy advocacy organizations.
- **Expert interviews:** Conducted interviews with experts and demand flexibility practitioners from over 25 industry organizations to develop a nuanced understanding of the barriers and their potential solutions.
- **Stakeholder survey:**[27] Received survey responses from 75 participants spanning the range of GEB stakeholders. The survey focused on prioritizing GEB deployment barriers and possible solutions.
- **National Lab workshops:** Conducted three workshops with National Lab building technology experts specifically to understand barriers and solutions related to GEB technology integration.

## Overview of the Barriers

Barriers exist at each point in the GEB value chain. Technologies must be developed, deployed, adopted, and utilized before their benefits can be realized. While the role of stakeholders varies at each of these steps, the presence of meaningful barriers at each step indicates that

25 For a discussion of EE barriers, see Shruti Vaidyanathan, et al., "Overcoming Market Barriers and Using Market Forces to Advance Energy Efficiency," ACEEE Report No. E136, March 2013. Also, Saul Rinaldi, Kara, Elizabeth Bunnen, and Sabine Rogers. "Residential Grid-Interactive Efficient Building Technology and Policy: Harnessing the Power of Homes for a Clean, Affordable, Resilient Grid of the Future." Prepared for National Association of State Energy Officials (NASEO), October 2019.

26 See Appendix C for detailed findings of the literature review.

27 See Appendix D for further detail on the stakeholder survey.

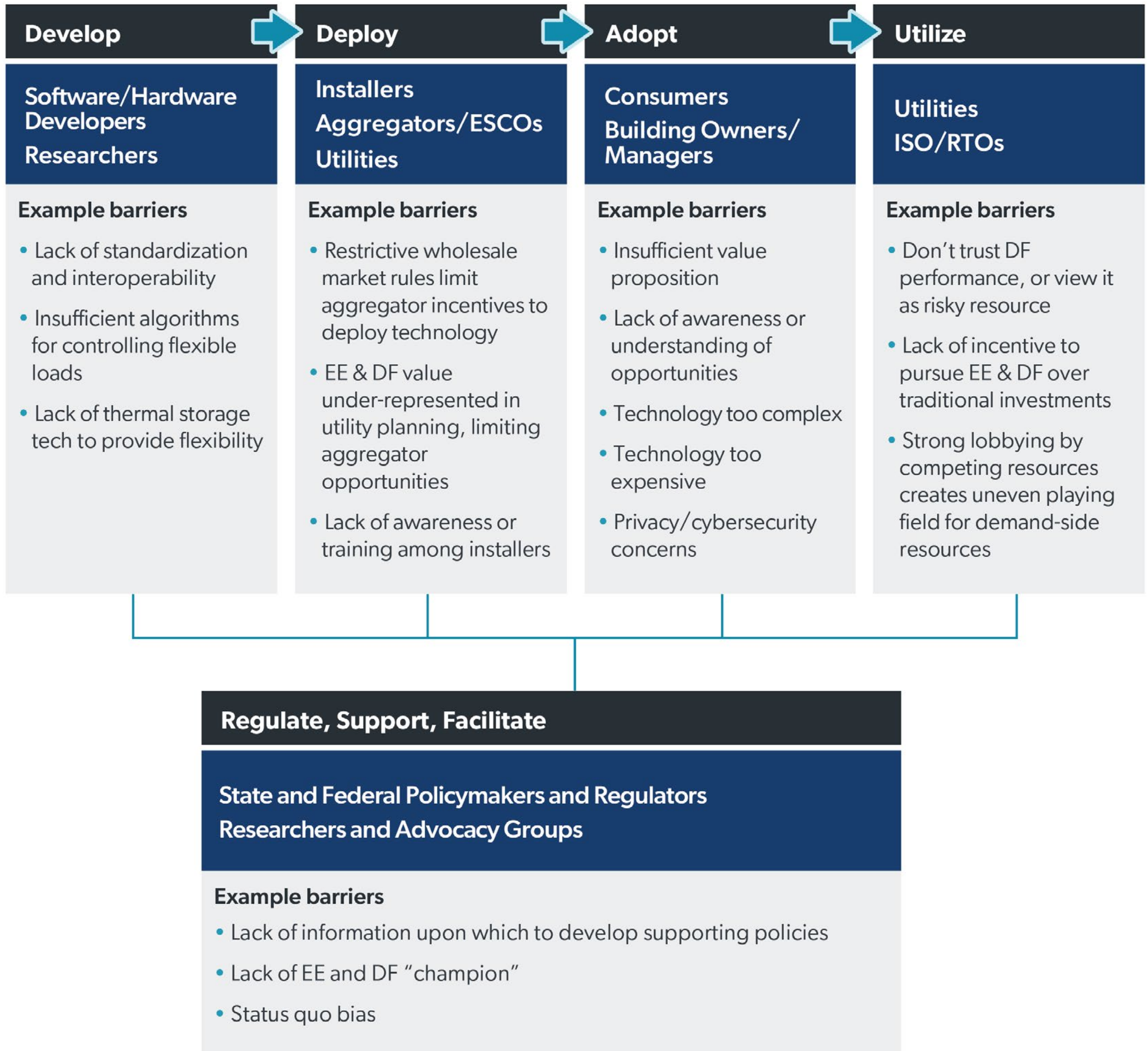



**FIGURE 10: GEB VALUE CHAIN AND KEY BARRIERS**

all stakeholders face challenges that must be overcome to fully realize GEB's potential. **FIGURE 10** summarizes example barriers at each point in the GEB value chain.

The value chain begins with the **development** of affordable, flexible thermal energy storage for HVAC and water heating, interoperable control technologies and smart algorithms, smart connected appliances, and other enabling infrastructure. Development barriers are particularly focused on building technologies that are user-friendly and can be integrated into buildings with other technologies.

Next, the technology must be **deployed** to consumers through building retrofits or new construction. For example, aggregators and ESCOs face the simultaneous challenge of equipping consumers with automating technologies and identifying meaningful opportunities to fully monetize the services that those technologies provide. Likewise, installers of smart appliances, equipment, and other GEB technologies are challenged to become familiar with – and skilled in – installing these potentially more complex technologies.

Consumer **adoption** of GEB technologies drives the GEB value chain. There must be a significant value proposition, financial or otherwise, for residential households and commercial building owners and managers to adopt GEB technologies. Reaching significant levels of adoption requires overcoming perceived risks (e.g., cybersecurity, complexity) and addressing insufficient participation incentive levels or the lack of consumer awareness of incentives.

Utilities and system operators (i.e., ISOs/RTOs) have the responsibility to **utilize** demand flexibility and ultimately realize the value of the services that it provides. Some of the most significant challenges were identified as existing at this point in the value chain. The challenges fundamentally relate to differences in how demand flexibility operates and is incorporated into planning activities compared to traditional infrastructure, as well as a perception among utilities and system operators that demand flexibility is riskier, even if many of the operational challenges can be addressed. Furthermore, there is a lack of financial incentives to overcome the differences and perceived risks, and to utilize demand flexibility as a grid resource.

Finally, federal, state, and local policymakers and regulators play a key role in **regulating, supporting, and facilitating** demand flexibility deployment across all points in the value chain. Research and advocacy groups augment some of these responsibilities. Challenges to overcome in this area relate to a lack of supporting information in regulatory proceedings regarding the benefits and performance capabilities of demand flexibility, which would serve as the basis to develop supporting policies and regulations, or a lack of political will to act on that information where it is available.

## The Top Barriers to GEB Deployment

The research conducted for this *Roadmap* identified the following as the most frequently cited barriers to GEB deployment. While these were identified as the top barriers to adoption and deployment, many others exist as well but are not directly discussed here.[28] Examples of other barriers include limitations on participation in wholesale markets, insufficient EM&V methods for demand flexibility, stakeholder processes that are dominated by incumbents, and incomplete cost-effectiveness evaluation methods. For each of the top barriers, we describe the particular concerns and challenges raised by industry stakeholders and identify where the barrier occurs in the GEB value chain. The barriers are presented in the order in which they appear in **FIGURE 10**.

### Lack of interoperability

Connectivity and interoperability are imperative for enabling GEB technology adoption at scale. Reliable, cyber-secure connectivity is crucial for ensuring reliable real-time delivery of grid services at the individual customer level. However, this seamless connectivity is not yet widespread: devices in GEB buildings – loads, storage, and generation – need to coordinate with each other both to manage flows of power, and to provide effective building and grid services. The communication technologies employed to enable this connectivity need to be highly capable, but also need to facilitate widespread interoperability. This means that any two devices in a building that might have a reason to communicate could do so, with little or no effort from the building owners, managers, or occupants.

The current lack of interoperability results in expensive integration efforts and discourages adoption or optimal use of GEB technology for both EE and demand flexibility. Similarly, common standards to enable interoperable

28 See Appendix C for further detail on the barriers identified in the development of this *Roadmap*. Also, see "State and Local Energy Efficiency Action Network" (2020). "Grid-Interactive Efficient Buildings: An Introduction for State and Local Governments." Prepared by: Lisa Schwartz and Greg Leventis, Lawrence Berkeley National Laboratory. Available at: https://emp.lbl.gov/publications/grid-interactive-efficient-buildings

communication between the building and the grid are lacking as well. Relatedly, communication with GEB technologies requires robust cybersecurity, given that the technologies can communicate with grid operators over public internet channels and directly impact the operation of the power system.

### EE and demand flexibility not included in planning activities

Relatively few utility integrated resource plans (IRPs) consider new, incremental EE additions as a resource option – and even fewer include demand flexibility.[29] And where EE and demand flexibility are considered, they often are modeled as a simple modification in system load to satisfy certain policy objectives, rather than conducting a more detailed analysis of the various options available, their likely adoption by consumers, and their cost-effectiveness. These shortcomings apply not only when generation investment decisions are being made through the IRP process, but also to grid planning when making transmission or distribution system investment decisions (which otherwise could consider demand flexibility as "non-wires solutions").

Planning activities overlook EE and demand flexibility for a variety of reasons. For example, utilities or ISOs leading the planning study often do not have financial or regulatory incentives to fully consider these options. In other cases, modeling constraints, or the lack of staff expertise in the benefits and unique operational constraints of demand-side resources, may limit the representation of EE and demand flexibility. As a result, cost-effective opportunities may be left on the table, increasing costs to consumers and limiting opportunities to provide these services.

### Technology too costly or complex

Consumers are hesitant to adopt energy-efficient technologies due to their high upfront cost. Demand flexibility functionality can add complexity to technology operation and present an additional barrier. This is particularly true in commercial buildings today, where the majority of existing demand response (DR) capability comes from non-automated (i.e., manual) peak load reductions. Some commercial building energy managers perceive that the complexity of automating technology will not actually reduce the amount of manual intervention required, since staff will still need to be trained on the technology and available to address issues. In other cases, commercial building managers have noted a preference for EE over demand flexibility, due to the passive nature of EE measures which do not require an event-based response. And while costs of many control technologies are by themselves relatively low, more advanced whole-BASs still require a significant upfront investment. Despite that investment providing a positive financial return to building owners and occupants, there sometimes is a lack of awareness of the likely cost-effectiveness of the investment, and the upfront costs can still be prohibitive in low-to-moderate income (LMI) households (see sidebar).

Among residential consumers, technological complexity may be a less significant barrier – utilities and aggregators are well equipped to install controls on HVAC units, smart thermostats generally do not have onerous installation and operational requirements, and occupants are able to more easily make changes on an ongoing basis. There is a need for integrated Smart Home Energy Management Systems, but interoperability requirements continue to be a challenge to coordinate control of two or more devices for demand flexibility in homes.

---

29 See, e.g., Andy Satchwell, "Analytical Approaches Used to Represent Demand Response Resources in Recent Electric Utility Integrated Resource Plans," May 1, 2017. Available at: https://eta-publications.lbl.gov/sites/default/files/lbnl_mi_ta_050117.pdf

## Demand flexibility and underserved communities

Recent stakeholder engagement efforts through the Alliance to Save Energy's Active Efficiency Collaborative identified a number of barriers related to demand flexibility, specifically in underserved communities.[29] According to the Alliance to Save Energy, low-income programs made up only 5% of total utility expenditures on electric demand-side management programs in 2017. Issues to be addressed include:

- Many demand flexibility programs depend on the participant having internet access, which can be a limiting factor among Low-to-Moderate-income (LMI) households.
- Renters may have limited access to EE opportunities, as landlords generally are not directly incentivized to reduce tenant electricity bills.
- Current demand flexibility marketing and outreach efforts often overlook rural and LMI households, resulting in distrust of utility messaging and less awareness of the potential opportunities and benefits of participating.
- EE resource standards, state targets, and cost-effectiveness screening methodologies often emphasize or require the pursuit of the lowest-cost EE and demand flexibility resources. This can limit contractor and utility offers to lower-income customers, as they often are viewed as "low yield" opportunities.
- Up-front costs or any requirements that technology adoption require the participant to take on debt can limit the accessibility of demand flexibility to LMI households.

### Consumers lack understanding or incentives

Consumers are likely to adopt GEB technologies and operate these technologies to provide demand flexibility with sufficient incentives. In most cases, financial incentives are the primary motivator for adoption. In other cases, consumers may be motivated by the opportunity to "be green," to contribute to a societal need for improved grid reliability, or to be early adopters of new energy technologies.

Although consumers may be willing to adopt GEB technologies, they are not likely to provide demand flexibility when the incentives to do so are outweighed by the perceived costs and risks. Often, financial incentives do not reflect the full value of the services that demand flexibility technologies can provide. For example, a demand flexibility program may compensate participants for avoided generation capacity costs without also providing a commensurate opportunity to monetize the value of load reductions that avoid distribution system costs. Similarly, retail rate designs – typically based on average costs – often do not reflect the time-varying nature of power system costs. Split incentives – the divide between building owners who would invest in the technology and tenants who pay electricity bills and would realize the benefits – also fall into this barrier category. A lack of utility or regulatory focus on engaging customers can contribute to a lack of awareness. Additionally, customers will seek assurance that their personal data is protected when utilizing GEB technologies.

30 For further discussion, see the Alliance to Save Energy/Active Efficiency Collaborative, Improving Equity and Inclusion in Energy Efficiency and Demand Flexibility Programs.

## Utilities and system operators often do not trust demand flexibility performance

Utilities and system operators are accustomed to planning for and operating a limited number of centralized power plants and automatic generator controls that typically provide hundreds of dispatchable megawatts at a single site. In contrast, demand flexibility may require the control of thousands (or hundreds of thousands) of individual, site-specific end-uses (e.g., residential air-conditioners) in order to provide impacts of a similar magnitude. Additionally, demand flexibility, absent certain control capabilities (e.g., ADR), largely lacks the virtually guaranteed response to grid needs that exists with traditional generators. For example, demand flexibility participants, particularly residential customers, sometimes have the option to "opt-out" of demand flexibility events, or simply could choose not to participate.

Nevertheless, differences between demand flexibility and traditional grid resources can be overcome. For example, studies have shown that event opt-out rates are low, and aggregators account for likely opt-out rates and other potential performance limitations when establishing load reductions to utilities and bidding demand flexibility into wholesale markets. Similarly, with sufficient data, utilities can develop statistically robust estimates of likely demand flexibility performance, similar to assumptions about the forced outage rate of conventional generators. Finally, deeper levels of demand flexibility from new technology could improve the reliability and magnitude of this growing resource.

Regardless of the improvements in demand flexibility performance and accountability, demand flexibility is perceived to be fundamentally different from the resources that utilities and system operators have traditionally relied upon. As long as perceptions of performance limitations exist, this will serve as a barrier to greater reliance on demand flexibility as a resource and limit how much of the demand flexibility resource potential can be realized.

## Utilities lack adequate regulatory incentives

As regulated monopolies, investor-owned utilities typically do not have sufficient financial incentives to pursue EE and demand flexibility under rate-of-return regulation. The lack of financial incentive is a particularly significant barrier, as utilities earn a return on capital investments in grid infrastructure but typically not on expenditures for demand-side resources since they usually are treated as an O&M expense. There also has been a difference in the investment scale between much larger investments in grid infrastructure (e.g., on the order of hundreds of millions of dollars) and smaller demand flexibility investments (e.g., on the order of tens of millions of dollars).

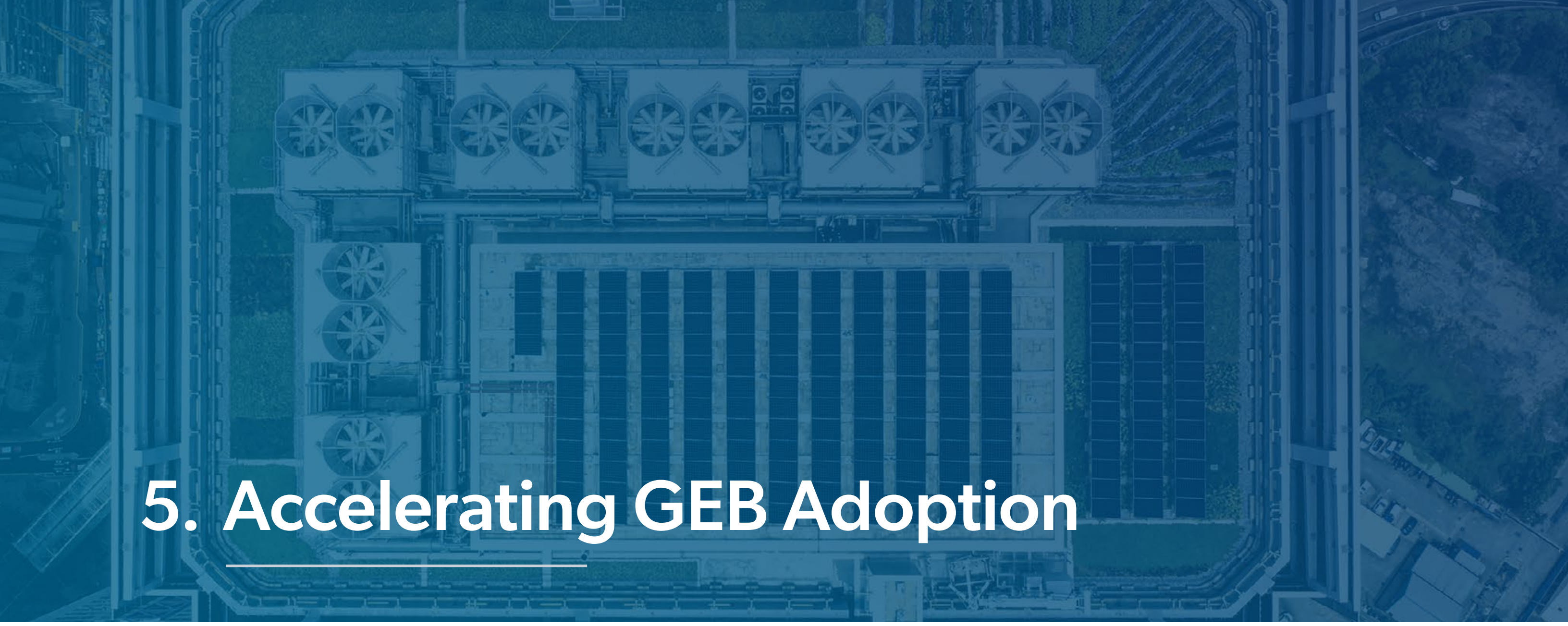
Alternative utility regulatory and business models can provide greater alignment between utility financial motivations and the successful deployment of demand-side programs, typically through financial incentives to meet EE and demand flexibility procurement goals, targets, or mandates. Opportunities to experiment and pilot different demand flexibility programs can also allow utilities to determine the design that can best meet their system and market needs. While there are select instances where alternative utility regulatory and business models have been implemented mostly for EE, they are not widespread among states and do not tend to incorporate demand flexibility.

## Missing demand-side "champion"

Organizations across the GEB value chain often do not have a culture in which demand-side options are a standard consideration. The demand-side often is an afterthought or an option to pursue once other opportunities have been exhausted. This implicit deemphasis of EE and demand flexibility is inconsistent with the benefits that can be provided by those resources, particularly given the important role that they can play in achieving climate-related corporate objectives.

Thus, a demand-side “champion” is needed at all points in the value chain. Demand-side resources will not get traction without a strong voice advocating for EE and demand flexibility initiatives. For example, the champion might be a state regulator that is focused on ensuring demand flexibility is considered as an alternative to utility supply-side investment decisions, or a utility executive who makes demand flexibility the focus of customer-centric product offerings, or a policymaker who introduces energy legislation with an EE focus, or a building manager who understands and articulates the benefits of EE or demand flexibility program participation within their organization.


20.0



# 5. Accelerating GEB Adoption

## Introduction

The recommendations in this *Roadmap* are organized around four "pillars" that are integral to supporting GEB adoption. Likewise, each of these pillars is critical to accelerating both demand flexibility and EE. However, since a number of prior reports have focused on EE adoption, accelerating both demand flexibility and EE, and achieving DOE's goal of tripling the EE and demand flexibility of buildings by 2030 relative to 2020 levels.[31] The recommendations in this *Roadmap* largely focus on either the critical elements that enable the optimization of a GEB or specific elements that will improve demand flexibility deployment and adoption:

1. Advancing GEBs through research, development, and data
2. Enhancing the Value of GEBs to Consumers and Utilities
3. Empowering GEB users, installers, and operators
4. Supporting GEB deployment through federal, state, and local enabling programs and policies.

The recommendations were informed by a review of the existing literature on building technologies; EE, DR, and demand flexibility programs; utility regulatory and business models; and other related topics. Importantly, the recommendations also reflect a range of stakeholder perspectives solicited through a survey of 75 practitioners, workshops with building technology experts at DOE and the National Labs, and in-depth interviews and group discussions with experts from over 25 organizations.

### **Pillar 1:** Advancing GEBs Through Research, Development, and Data

Advances in data processing, cloud computing, communications, sensors, and controls are resulting in greater optimization of operations of buildings and improved EE and demand flexibility capabilities. To readily implement and scale GEBs, efficient technologies equipped with advanced control capabilities must become more user-friendly with lower price points. R&D is needed at both the individual equipment level, as well as whole-building integration of building energy systems and DERs in order to fully optimize GEB potential and demonstrate its cost-effectiveness. Research is needed to improve technology

31 For example, see the EPA's "National Action Plan for Energy Efficiency," July 2006. Also, State and Local Energy Efficiency Action Network, "Grid-Interactive Efficient Buildings: An Introduction for State and Local Governments," prepared by Lisa Schwartz and Greg Leventis, Lawrence Berkeley National Laboratory, April 2020.

interoperability and integration, along with specific hardware improvements. In addition, M&V improvements are needed to overcome barriers to assessing the performance of next-generation demand flexibility programs and markets, critical to securing confidence in GEBs as a grid resource.

### Pillar 2: Enhancing the Value of GEBs to Consumers and Utilities

Consumers are increasingly adopting smart technologies and other DERs, often because of the convenience, additional control, and safety features of the technologies. However, consumers need a compelling reason to use these technologies to transform their buildings into grid assets and provide demand flexibility. Consumer-focused recommendations in this pillar are oriented around two ways of enhancing the value proposition: price-based options (e.g., time-varying retail rates) and incentive-based programs (which can include non-financial incentives).

Similarly, utilities and aggregators must be able to benefit from the value of GEBs in order to create and promote customer opportunities. For regulated, investor-owned utilities, this could involve the introduction of new regulatory and business models that better align corporate and shareholder objectives with those of their customers by providing financial incentives for GEB deployment. Additionally, incorporating demand flexibility into existing utility planning and procurement can enhance its value in reducing future supply-side investment costs and risks. This, combined with improvements in wholesale market design, would create new opportunities for aggregators to expand demand flexibility deployment.

### Pillar 3: Empowering GEB users, installers, and operators

Realizing the full GEB opportunity ultimately depends on building owners and electricity customers choosing to adopt efficient technologies with advanced control capabilities and to subsequently participate in demand flexibility programs. A deeper understanding of consumer preferences, perceptions, and motivations to invest in these technologies can inform better technology design and program marketing. Additionally, intuitive and capable tools that co-optimize energy, non-energy, and financial benefits can improve GEB technology investment and building operational decisions by equipping building owners, operators, and technology installers with the information needed to make informed decisions. Furthermore, fundamental improvements are needed related to workforce training on smart technologies for building operators, equipment installers, and repair technicians so building technologies can be installed, operated, and maintained for optimal performance.

### Pillar 4: Supporting GEB deployment through federal, state, and local enabling programs and policies

Electricity is one of the most highly regulated sectors of the U.S. economy. Effectuating change in the electricity sector often requires policy intervention, and major new program and policy initiatives present a significant opportunity to incorporate GEBs in both the near- and long-term. Specifically, demand flexibility is a significant opportunity to meet renewable and decarbonization goals. This pillar focuses on four areas for state and federal policy and program development that could help accelerate GEB deployment: "leading by example" in the federal, state, and local government buildings sector, expanding funding and financing options, codes and standards for buildings and appliances, and establishing goals, targets, or mandates related to resource procurement.

## Addressing the Barriers

The recommendations in this *Roadmap* were developed specifically to address the top barriers to demand flexibility described in Chapter 4. **FIGURE 11** summarizes how the recommendations directly or indirectly address those barriers.

## Elements of Each Recommendation

The remainder of this chapter includes a profile of each recommendation, consisting of the following elements. Additional supporting information is provided in Appendix D. The References section includes suggested further reading related to each of the 14 recommendations.

- **Overview:** What recommendation is being proposed? What is the goal of the recommendation? What are potential obstacles to its success?
- **Key actions:** Tactically, what needs to be done to execute the recommendation? For each action, the entities with primary responsibility for its implementation are identified (see legend below).
- **Timing:** What is a likely timeline for achieving success?

**LEGEND**

| | |
|---|---|
| | Government (federal, state, local, incl. relevant regulatory authority) |
| | Utility |
| | Market operator (ISOs, RTOs) |
| | Implementer (aggregator, ESCO, installer) |
| | Technology Developers |
| | Researcher (incl. policy advocacy) |

| Recommendation | TOP BARRIERS TO GEB DEPLOYMENT AND ADOPTION: Lack of interoperability | DF not fully included in planning | Tech too costly or complex | Consumers lack incentive or understanding | Utilities & system operators do not trust DF performance | Utilities lack regulatory incentive |
|---|---|---|---|---|---|---|
| **Pillar 1: Advancing GEBs through research, development, and data** | | | | | | |
| Develop/accelerate deployment of GEB technologies | | | ✓✓ | ✓ | | |
| Accelerate technology interoperability | ✓✓ | | ✓✓ | ✓ | | |
| Improve access and use of DF data | | | ✓ | ✓ | ✓✓ | |
| **Pillar 2: Enhancing the value of GEBs to consumers and utilities** | | | | | | |
| Develop innovative incentive-based programs | | | | ✓✓ | | |
| Expand price-based program adoption | | | | ✓✓ | | |
| Introduce incentives for utilities to deploy demand-side resources | | | | | | ✓✓ |
| Incorporate DF into resource planning | | ✓✓ | | | | ✓ |
| **Pillar 3: Empowering GEB users, installers, and operators** | | | | | | |
| Understand user interactions with GEBs and role of technology | | | ✓ | ✓ | ✓ | |
| Develop GEB design & operation decision-making tools | ✓ | | ✓✓ | | | |
| Integrate smart technology training into existing programs | ✓ | | ✓ | | | |
| **Pillar 4: Supporting GEB deployment through government programs & policies** | | | | | | |
| Lead by example | | | | ✓ | ✓ | |
| Expand funding and financing options | | | ✓✓ | ✓ | | ✓ |
| Consider use of codes & standards | ✓ | | ✓ | ✓ | | |
| Consider implementing state targets/mandates | | ✓ | | | | ✓ |

**FIGURE 11: ROADMAP RECOMMENDATIONS FOR MITIGATING THE TOP GEB BARRIERS**

✓✓ Addressed directly ✓ Addressed indirectly

PILLAR 1

# Advancing GEBs Through Research, Development, and Data

In order for GEBs to be readily implementable and scaled, efficient technologies equipped with advanced control capabilities must become more user-friendly and available at a lower cost. Pillar 1 focuses on research that is needed to improve technology interoperability and integration, along with specific hardware improvements.

RECOMMENDATION 1

## Research, Develop, and Accelerate Deployment of GEB Technologies

### Overview

**Objective:** Increase the capability, availability, ease of use, and cost-effectiveness of high-impact efficient building technologies that provide demand flexibility in residential and commercial buildings.

Building technologies with high demand flexibility potential span both early-stage, high-reward technologies that need further development, as well as commercially available technologies that could be adopted at a faster rate with improvements in standardization and ease of integration. To improve building operational efficiency and make loads more flexible, research, development, and deployment of both building hardware equipment and software in the form of sensing and control systems are needed. Programs are rapidly evolving from DR for limited duration and frequency to the ongoing optimization of building equipment in sync with the temporal and locational variation of renewable supply resources. New technologies, sensors, control, and communication systems are needed to receive and respond to dynamic prices and other grid signals (see discussion of **FIGURE 9** in Chapter 3 and Appendix E).

### Key Actions

- **Set R&D targets to make grid-interactive equipment cost-effective and easier to install and operate, prioritizing thermal energy systems.** R&D at the device level needs to incorporate both hardware and software improvements. Across all building equipment, there is a need for research and field validation focused on reducing the cost and increase the reliability of device-specific grid-interactive controls and communication. Since thermal systems provide the greatest potential for demand flexibility, these systems should be prioritized, with a particular focus on grid-interactive heat pump heating and cooling systems, given the importance of this technology in meeting decarbonization goals through efficiency and electrification.

- **Explore opportunities to integrate and control affordable thermal energy storage.** R&D is needed to understand how to integrate emerging thermal energy storage technologies and modular components with various types and sizes of HVAC and water heating systems. Additionally, research, development, and field testing of the algorithms to control these integrated systems is needed. Research is also needed to develop measurement protocols and standards to evaluate these TES systems and devices. This R&D is important because thermal storage technologies are designed with different materials in different shapes and sizes, and research is needed to ensure the TES is efficient and affordable.

- **Support development and field testing of user-friendly, affordable integrated whole-building control and**

**grid service delivery.** Single end-use load control technologies can be aggregated as a first step towards providing increased demand flexibility. However, to fully optimize a GEB, the integration of multiple end-uses and DERs is needed in both residential and commercial buildings as well as in various market segments (e.g., retail, grocery, multifamily residential), which requires developing lower cost and more accurate sensing options and system-wide control algorithms. Development, training, and calibration of cost-effective predictive control techniques that are accurate, robust, and easy to deploy will support this objective. Many of these technologies will benefit from incorporating new methods for artificial intelligence and machine learning. Research is also needed on how a SHEMS or BAS integrates building loads with other DERs such as EVs, PV, and electric storage. (see Pillar 1, Recommendation 2 on interoperability).

- **Develop and demonstrate integrated low-carbon building retrofit packages that leverage GEBs.** Utilities are exploring opportunities to move EE programs beyond widget retrofits to integrated system packages. As the need for demand flexibility increases, integrated system packages will need to include technologies and controls that support grid integration. There also is a need for retrofit packages to electrify thermal end uses with built-in demand flexibility capability. Building retrofits, especially using low-cost technology solutions, are key to achieving equitable outcomes as older building stock is more likely to serve marginalized communities.

## Making Technologies that Integrate with the Grid

Through collaboration with researchers, technology developers, and utilities, heat pump water heaters installed with the CTA-2045 modular communications interface have successfully demonstrated their ability to be grid-interactive resources. CTA-2045 offers a standard physical socket and supports several communication protocols. Following lab and field testing from 2012-2015 with water heaters, thermostats, and electric vehicle chargers, Bonneville Power Administration and Portland General Electric in 2016-2017 implemented successful pilots and developed a business case for market transformation. In May 2019, Washington State passed legislation requiring all electric storage water heaters sold in the state to have ports compliant with ANSI/CTA-2045-A. (see: https://app.leg.wa.gov/RCW/default.aspx?cite=19.260.080). AHRI Standard 1380 also supports the use of CTA-2045 and OpenADR for variable capacity HVAC systems. See Appendix E for more details.

### TIMING FOR RECOMMENDATION 1
**Research, Develop and Accelerate Deployment of GEB Technologies**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Evaluate HVAC and water heating technologies and develop algorithms. | Evaluate how to integrate and control thermal energy storage with HVAC and water heating. | Support field testing of affordable integrated whole-building control and grid service delivery. |
| Evaluate and support deployment of connected flexible devices for appliances, electronics, and MELs. | Develop and demonstrate integrated low-carbon flexible building retrofit packages. | Develop measurement standards for TES systems. |

**RECOMMENDATION 2**

## Accelerate Technology Interoperability to Optimize Efficiency and Demand Flexibility Performance

### Overview

**Objective:** Ensure that end-use devices, DERs, and multiple buildings can interoperate and coordinate to provide building and grid services, with minimum effort from service and technology providers, residential homeowners, commercial owners, managers, and occupants.

A GEB requires interoperability at many levels; improvements in interoperability of integrated devices within buildings, between buildings, and between buildings and the grid are needed. For fully optimized demand flexibility, individual technologies (e.g., lighting, air conditioning) need to coordinate with each other, as well as with DERs (e.g., battery storage, solar PV) to manage and optimize flows of power and to provide effective building services. Furthermore, GEBs need to interact with utility grids to provide services, and in some cases, multiple buildings may be coordinated to provide these services. However, barriers to 'plug-and-play' interoperability at all levels hinder the realization of GEBs at scale. Increased interoperability is key to reducing installation, configuration, and system maintenance costs. In addition, interoperability will streamline the delivery of efficiency and comfort benefits, as well as overall convenience and usability for customers.

A key implementation challenge is that interoperability is not aligned with current market practices. Manufacturers and product providers must have confidence that the demand for interoperable technologies will provide enduring benefits and not erode their competitiveness or market share. Manufacturers may also be reluctant to grant permissions to third-party controls, and they may void warranties or require additional maintenance if third-party controls are used.

### Key Actions

- **Accelerate adoption of existing open standards, particularly at the application layer.** Standards exist and are being used today by some technology vendors at the application and networking levels. However, ubiquitous usage of existing open standards is needed at all software layers to enable communication and operation for GEBs. The application layer is the primary interface for interacting with communication and control systems and services; hence it is important to provide an interoperable environment at this layer (further discussed in Appendix E). Existing open standards at the application layer include BACnet, HTTP, OpenADR, and CTA-2045. Open standards also exist at the networking layer (e.g., TCP/IP) and the data layer (e.g., Ethernet, Wi-Fi, Zigbee).

- **Identify additional open standards needed at the application layer across grid services.** Existing standards such as OpenADR and CTA-2045 may not be sufficient to capture the information requirements across all grid services at the device, building, and multi-building levels.

- **Streamline delivery of GEB applications and capabilities by providing standard solutions for data interpretability.** Technical interoperability must be complemented with semantic interoperability so that the data (topological, physical, and operational relationships) can be understood with minimal manual human effort. This requires developing a semantic standard that could be used by technology vendors to seamlessly integrate across solutions.

- **Provide system and device level reporting capabilities.** System and device-level reporting capabilities are needed so that parameters relevant to grid-interactive control (e.g., status, operational mode, power consumption) can be accessed by other services and applications (e.g., via an open application programming interface (API)). This can be done by developing standardized reference specifications and requirements for device reporting by system type, such as for HVAC, thermostats, water heaters, and other devices.

- **Enable users to provide control permissions to trusted third-party applications and services while ensuring cybersecure controls and communications.** Grid-interactive control sequences that integrate across systems, devices, or multiple buildings, may be determined by supervisory or extra-supervisory platforms. For optimal grid response, these controls must be granted "permission to operate" by owners, as well as the original or primary system provider. Similarly, it is critical that these systems use best practices for cybersecurity.

- **Field validate the benefits of enhanced interoperability.** Field demonstrations are needed to validate benefits, including reduced labor and cost to configure GEBs, the quality, magnitude, and consistency of grid services delivered, and the multi-stream value to users (e.g., efficiency, comfort, ease of use). This validation should include options for LMI households and other communities where broadband access may be limited.

- **Explore methods to rate or score interoperability of devices and buildings.** Develop mechanisms to facilitate a scoring or interoperability rating. This would support market adoption by highlighting the capabilities of GEB technologies and systems.

## Connected Home over IP (CHIP) Industry Working Group

Amazon, Apple, Google, and the Zigbee Alliance joined together to promote the formation of the CHIP Working Group. This working group mostly focuses on technology for residential applications and includes use cases that are not related to energy (e.g., security, entertainment). The goal of the CHIP project is to simplify development for manufacturers and increase compatibility for consumers. The Industry Working Group will develop and implement a new open-source, unified connectivity protocol. The project aims to make it easier for device manufacturers to build devices that are compatible with smart home and voice services such as Amazon's Alexa, Apple's Siri, Google's Assistant, and others. This example is provided to illustrate how alliances can facilitate interoperability in technology development (CHIP, 2020). Similar efforts are needed in the energy space.

### TIMING FOR RECOMMENDATION 2
**Accelerate Technology Interoperability to Optimize Efficiency and Demand Flexibility Performance**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Develop strategies to promote use of open standards.<br>Conduct field evaluations of interoperability.<br>Develop and require reference specifications for device reporting. | Support use of semantic interoperability.<br>Develop Smart Grid Ready rating or scoring system. | Evaluate needs for new communication standards. |

**RECOMMENDATION 3**

## Collect and Provide Data and Develop Analytical Methods for Benchmarking and Evaluating Demand Flexibility Technology and Whole Building GEB Performance

### Overview

**Objective:** Ensure that GEB technology, building performance, and customer cost-benefit data are easily accessible, and improve and standardize analytical methods.

GEB field performance assessments and metrics are needed to enable grid operators to trust the ability of demand flexibility to reliably deliver grid services. This includes developing and evaluating the use of standard baseline M&V methods to measure demand flexibility, as well as and collecting field data on demand flexibility building performance. Also, building owners and operators are unwilling to invest in technology without a clear value proposition based on proven technology benefits. Demand flexibility benchmark data sets, load shapes, and metrics are needed across all building sectors to provide relevant, comprehensive data for GEB technology performance evaluation. To draw meaningful conclusions from the data that can be relied upon by grid operators, utilities, and customers, there is a need for statistically significant data sets at scale and across different dimensions of building type and time (e.g., hourly, daily, annually).

Key implementation challenges include managing privacy and cybersecurity with widespread data accessibility. Users may have privacy or security concerns related to the transmission and storage of whole-building and specific end-use equipment and system data. Utilities, aggregators, technology providers, and DER service providers may also worry about liability related to sharing customer data. Additionally, providing granular data would require robust data storage systems. Technology providers must carefully balance these concerns with the need to provide easy access to data for customers, grid operators, aggregators, and performance evaluators. A challenge specifically related to analytical methods is establishing appropriate baselines, particularly with multiple programs and rate designs, and when demand flexibility is used routinely.

### Key Actions

- **Develop standard metrics and methods for data collection, data analysis, and measurement and verification (M&V) of demand flexibility technologies and strategies.** M&V methods for EE and DR have been developed for many years and are evolving toward increased use of automation and hourly meter data (e.g., "advanced M&V" or "M&V 2.0" with and without control groups). Similarly, hourly data, and in some cases sub-hourly data, and advanced telemetry are needed for demand flexibility market settlement. These metrics along with new and scalable evaluation methods must also be developed for the full complement of grid services that buildings can provide. Simplified approaches are needed for demand flexibility performance assessments at the whole building and system/equipment level and for multiple demand flexibility modes (e.g., shed and shift in combination).

- **Expand EE benchmark dataset and benchmarking tools to incorporate demand flexibility.** There is a long practice of collecting total energy use normalized by floor area to compare the energy performance of buildings. These data are made available through tools like the EnergyStar benchmarking tool and the Building Performance Database. Similar data are needed to evaluate information critical for valuing demand flexibility: electric load shapes, peak demand (W/sq. ft.) reduction capability, and the performance of DR and demand flexible technologies. These data are also needed to evaluate the reliability and consistency of the grid services that flexible demand technologies can deliver, as well as the metrics by which these technologies should be evaluated.

### TIMING FOR RECOMMENDATION 3

**Collect and Provide Data and Develop Analytical Methods for Benchmarking and Evaluating DF Technology and Whole Building GEB Performance**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Develop standard methods for DF data collection and M&V. | Develop demand flexibility benchmark data sets and tools.<br><br>Contribute to benchmarking tools to evaluate DF performance. | Maintain and evaluate ongoing use and needs for benchmarking tools. |

PILLAR 2

# Enhancing the Value of GEBs to Consumers and Utilities

Consumers need a compelling reason to use smart technologies to transform their buildings into grid assets and provide demand flexibility. Similarly, utilities and aggregators must be able to benefit from the value of GEBs in order to create and promote customer opportunities. Pillar 2 focuses on ways of enhancing the GEB value proposition to consumers, utilities, and aggregators.

RECOMMENDATION 1

## Improve and Expand Innovative Customer Demand Flexibility Program Offerings

### Overview

**Objective:** Increase the availability and adoption of innovative, consumer-oriented demand flexibility programs offered by utilities, aggregators, and competitive retail energy providers.

Incentive-based demand flexibility programs offer consumers financial compensation to provide the grid with more flexibility. Incentive-based program compensation can occur through means that are separate from price-based programs delivered via retail rates. For example, consumers may be offered an upfront and/or monthly incentive payment, "reward points," or rebates to promote demand flexibility program enrollment and participation. Building on the success in EE and DR program design and implementation, innovative incentive-based programs could create new opportunities for engaging a variety of consumers to provide increased load flexibility. However, utility DSM budgets may limit the extent to which new programs can be offered, in addition to the typical practice of multi-year DSM budgeting cycles that limit program design flexibility and short-term innovative programs. Robust business cases can be developed with a holistic view of benefits, including recognizing both power system benefits and non-energy benefits that may accrue to consumers (e.g., in the form of improved productivity, comfort, and health).

### Key Actions

- **Design and market demand flexibility programs with a focus on consumer preferences.** Successful demand flexibility programs typically offer a clear and simple financial reward, do not require the consumer to make a significant up-front financial investment by leveraging existing technology or capabilities, and promote the provision of non-grid benefits (e.g., helping the environment). Market research can help to inform the program features that are most attractive to customers and the customer segments that are the best candidates for enrollment. This step should be accompanied by tailored customer outreach and education.

- **Package demand flexibility with other attractive consumer offerings.** Consumers may be more willing to participate in an incentive-based demand flexibility program if it is part of a broader "package" that is attractive to consumers. For instance, a free or highly subsidized technology such as a smart thermostat would offer other consumer benefits, like attractive aesthetics, remote-control features, and EE savings.

- **Consider additional value streams in incentive-based demand flexibility program compensation.** Many existing demand flexibility programs only compensate participants for a subset of the value that demand flexibility measures could provide (e.g., reduced energy costs). Programs that capture more of the "value stack" (e.g., by combining generation benefits with transmission and distribution (T&D) benefits) without noticeably increasing performance requirements will provide greater overall financial compensation to participants.

- **Review existing DR programs for opportunities to modernize design.** The design of some DR programs, such as interruptible tariffs for large customers, has remained largely unchanged for many years. There may be opportunities to revise program participation rules and compensation structures to improve their attractiveness to potential participants, increasing enrollment while also improving utilization of the program.

- **Develop partnerships between utilities and aggregators to help implement incentive-based demand flexibility programs.** Aggregators do not always face the same program design constraints as utilities (e.g., aggregators can shield participants from non-performance penalties in ways that utilities typically are not allowed). Some utilities solicit RFPs for demand-side resources that can meet specific criteria (i.e., a specified load reduction during certain times of the day) that aggregators can respond to.

- **Research and socialize data on innovative demand flexibility programs.** Assemble a publicly-available catalog of innovative demand flexibility program offerings and highlight emerging best practices. Research could focus on clear marketing and communication to build awareness of the benefits of demand flexibility and boost participation.

- **Encourage and publicize innovative demand flexibility programs and pilots.** Sponsor pilots that test innovative, under-researched demand flexibility program options, with a focus on methods that increase customer engagement or provide a broader range of value streams. The use of public funding sources may include a requirement that applicants demonstrate the proposed pilots address a specific gap in the industry's understanding and that data and results will be made publicly available (while anonymizing the data to address privacy concerns).

### Innovations in DF Program Design

Hawaiian Electric (HECO) Grid Services Purchase Agreements: HECO issued an RFP for services from DERs (including demand flexibility). The RFP defines specific performance criteria that must be met from aggregated resources. This is a technology-agnostic approach that recognizes the ability of aggregated, small resources to provide the same benefits as grid-scale resources.

ConEdison DR Programs: ConEdison offers a Commercial System Relief Program (CSRP) and a Distribution System Relief Program (DSRP). CSRP is utilized to address bulk-system needs, while DSRP addresses local needs on the distribution system. Customers are allowed to participate in both programs through a single aggregator, thus receiving compensation for providing multiple types of services. This highlights one approach to "stacking" multiple value streams from a single participant.

## TIMING FOR RECOMMENDATION 1

**Improve and Expand Innovative Customer Demand Flexibility Program Offerings**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Refine existing programs, tariffs.<br>Design and test new programs. | Introduce new programs at scale. | Refine, update, and revisit new program options on an ongoing basis. |

**RECOMMENDATION 2**

## Expand Consumer Knowledge and Consideration of Price-Based Programs

### Overview

**Objective:** Increase availability and consumer adoption of price-based programs.

The widespread adoption of price-based programs, especially dynamic, time-varying retail rates, provides consumers an opportunity to monetize demand flexibility benefits and better manage electricity bills. In the future, time-varying retail rates could be the foundation for "transactive energy," whereby building technologies can receive and respond directly to price signals that reflect real-time grid conditions. While most utilities offer some form of price-based program, the pricing may not align with carbon reduction goals.[32] In most cases, customer enrollment remains low. In jurisdictions with smart meters[33] that enable time-varying rates to be offered cost-effectively at scale, there is an opportunity to improve the design and adoption of price-based programs beyond today's levels through consumer education, understanding enrollment drivers, and design for full scale deployment focused on meeting both capacity and carbon reduction goals. Actions related to expanding price-based options are particularly relevant for residential and small commercial customers that presently have fewer time-varying rate opportunities than larger commercial customers.

Traditionally, a key challenge to price-based programs are concerns about adverse impacts on vulnerable consumer segments (e.g., low-income, elderly consumers). There are also apprehensions among utilities and regulators that consumers will not understand time-varying rates, limiting their ability to respond to the rates. While these concerns are not unwarranted, a number of pilots and studies demonstrate that these impacts are minimal.[34] Additionally, because utility rates are designed to be revenue neutral, changes to rate design typically will cause some customers' bills to decrease and others to increase. Utilities and regulators may hesitate to implement a new price-based program to avoid potential bill increases for some customers, in particular. Continued dissemination of the positive experience with previous well-implemented time-varying rates, as well as strong leadership among regulators and utilities, is needed to overcome these perceptions and realize the benefits of time-varying rates.

### Key Actions

- **Consider customer adoption of EE and demand flexibility measures as part of broader rate design objectives.** While the overarching principle of retail rate design is that rates should reflect costs, there is a broad range of rate design options that can satisfy this principle and other objectives to promote EE and demand flexibility measure adoption (e.g., improved customer bill management, consistency with state policy objectives like promoting decarbonization). Importantly, state regulators will consider these objectives relative to tradeoffs across other criteria such as simplicity, equity and fairness (e.g., avoiding within and cross-class subsidization), and affordability.

32 This could occur, for example, if TOU rates result in electricity consumption being shifted from times when lower marginal GHG emissions rates to times with higher marginal GHG emissions rates.

33 "Interval meters" are capable of measuring usage in granular time-scales, such as hourly measurements. While larger commercial customers typically have been equipped with interval meters for decades, advanced metering infrastructure (AMI), or "smart metering," has only recently become widespread for the residential class.

34 A recent study shows that low- and middle-income (LMI) customers in Maryland respond to time-of-use pricing at a comparable magnitude to non-LMI customers. See Sergici, et al., "PC44 Time of Use Pilots: Year One Evaluation," prepared for the Maryland Joint Utilities, September 15, 2020.

- **Understand customer enrollment and bill impacts.** Impacts on customer bills (for both participating and non-participating customers) and system costs should be analyzed. Testing different enrollment methods (e.g., voluntary vs. default) can help utilities understand what motivates customers to enroll in price-based programs and how to achieve higher adoption rates. In particular, it will be important to understand the extent to which bills may change for LMI customers, DG customers, or other customer segments for which specific, and possibly competing, policy objectives may exist.

- **Take an inclusive approach to marketing the new options to consumers.** Marketing materials and outreach teams and initiatives should be assessed to ensure that they reflect the demographics of the various customers and communities they serve. This includes developing outreach materials in languages other than English and partnering with organizations trusted by local communities.

- **Plan for full-scale deployment.** Price-based program pilots should be conducted as the first phase of a broader plan for full-scale deployment and not a standalone activity. Pilots create an opportunity to collect information on customer preferences and persistence of savings, as well as utility system preparedness, to inform the subsequent phases. Key deployment decisions will need to be resolved to successfully achieve full-scale deployment.

### Default deployment of time-varying rates

One way to achieve widespread adoption of time-varying rates is to deploy them as the default rate option, with an opt-out provision. Some utilities have begun this transition. In California, SMUD and the California investor-owned utilities (IOUs) are moving forward with deploying time of use (TOU) as the default residential rate structure. Consumers Energy (Michigan) and Xcel Energy (Colorado) have received regulatory approval to do the same. Fort Collins in Colorado has rolled out TOU rates on a mandatory basis. Pepco and BGE have deployed peak time rebates on a default basis in Maryland. In many cases, the push to do so has come from the regulator in order to address renewables integration objectives and capitalize on the functionality of smart metering deployments.

**TIMING FOR RECOMMENDATION 2**
**Expand Consumer Knowledge and Consideration of Price-Based Programs**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Develop/socialize new rates designs.<br><br>Initiate pilots (if necessary). | Complete pilots (if necessary).<br><br>Introduce rates at a scale. | Complete rate transition plan.<br><br>Refine rate based on feedback. |

**RECOMMENDATION 3**
## Introduce Incentives for Utilities to Deploy Demand-Side Resources

### Overview

**Objective:** Align the utility's financial incentives with the deployment of cost-effective, demand-side resources.

Under traditional cost-of-service regulation, investor-owned utilities have a financial incentive to prioritize large supply-side capital investments over demand-side resources such as EE and DR, because the utility's earnings are typically tied to the regulated rate of return on capital investments. Alternative regulatory frameworks – referred to broadly here as performance-based regulation (PBR) – can motivate utilities to explore and pursue demand-side programs by more explicitly linking successful deployment and utilization of EE and DR resources with financial incentives and encouraging their use by strengthening cost-containment incentives. Greater alignment of wholesale market opportunities and demand-side potential may also be an incentive for both utilities and aggregators to deploy demand-side resources in wholesale electricity markets.

Under PBR, it is important to determine an appropriate level of incentive in dollar or basis point terms. The incentive level must be meaningful and commensurate with risks for utilities to act. At the same time, incentives must not distort market signals, or risk resulting in large inefficiencies and high consumer costs. A multi-phase rollout allows regulators to adjust the incentive level and modify program design to increase uptake.

In some states, the M&V and regulatory requirements to demonstrate savings from EE programs are considered too burdensome for performance incentive and shared savings mechanisms to motivate expanded deployment, or can result in protracted litigation. Concerns exist that this same burden will extend to utility shareholder financial incentives for demand flexibility. Simplified and transparent processes can help mitigate this issue.

### Key Actions

- **Identify and evaluate the appropriate incentive mechanisms to encourage investment in demand-side programs.** These alternative mechanisms may include one or more of the following:
  - **Decoupling mechanism.** Allows the utility to collect sufficient revenue to cover its fixed costs regardless of the level of retail electricity sales.
  - **Lost Revenue Adjustment Mechanism (LRAM).** Compensates the utility for the net lost revenue associated with its demand-side programs.
  - **Performance incentive mechanism.** The utility may receive additional earnings or rate of return incentives for meeting a pre-determined EE or demand flexibility performance goal.
  - **Multiyear rate plans.** Less frequent rate cases and an attrition relief mechanism that automatically adjusts rates or revenues between rate cases (based on cost drivers like inflation and customer growth) can be coupled with performance incentive mechanisms to further encourage demand-side measures.
  - **Rate of return incentives**. The utility capitalizes its spending on demand-side programs similar to how it rate-bases supply-side expenditures, earning an authorized rate of return on demand-side spending.
  - **Shared net benefits incentives.** The system financial benefits from demand-side programs are shared between the customers and the utility. Benefits are oriented around cost savings due to deferred infrastructure investment and maintenance requirements.
- **Assess whether and how the incentive mechanisms of interest may comport with existing laws and regulations.** Depending on the jurisdiction, certain incentive mechanisms may require new legislation and/or regulatory frameworks before they can

be implemented. Experiences from EE programs can provide useful guidance and lessons learned.

- **Develop key design parameters and metrics for the adopted incentive mechanisms, as well as the process for setting specific program targets.** Parameters and metrics should be clear, transparent, and objectively measurable and verifiable. Program targets should be outcome-oriented, compatible, and consistent. Utility shareholder incentives for the successful achievement of EE goals and targets are common, and results can serve as useful examples for demand flexibility program targets.

- **Evaluate customer impacts when estimating the cost-effectiveness of the new incentive mechanism.** Consider customer protection measures, especially for vulnerable customers. These measures may include limiting rate increases to a fixed percentage, capping program expenditures, and guaranteed bills.

- **Perform research studies and provide technical assistance.** Studies on the feasibility and effectiveness of PBR in the context of demand-side program goals and targets can help inform regulators, utilities, and other stakeholders of how PBR can help deploy demand-side resources and reduce utility costs.

- **Consider underserved communities when establishing performance metrics.** Performance incentive mechanisms could tie utility financial incentives to the level of participation in EE and demand flexibility offerings by underserved communities.

- **Identify opportunities for improving demand flexibility access to wholesale markets.** FERC Orders 719, 745, 841, and 2222 were introduced with the intent to provide improved access to wholesale markets for demand flexibility and other DERs. FERC, ISOs, RTOs, and stakeholders can continue to assess wholesale market participation rules in order to ensure that demand flexibility resources are eligible to provide all applicable wholesale market products and be compensated accordingly.

### Green Mountain Power "Energy Services Utility" business model

Green Mountain Power, a regulated, investor-owned utility in Vermont, considers itself an "energy service utility" and offers direct financial rebates on a number of consumer products that support renewables integration efforts and promote electrification of the grid through increased adoption of more efficient electrified end-uses, like air-source heat pumps. The utility leases numerous consumer products, including a heat pump water heater that is controllable by the utility for demand flexibility, via its online marketplace.

## TIMING FOR RECOMMENDATION 3

**Introduce Incentives for Utilities to Deploy Demand-Side Resources**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Review, revise, and adopt PBR frameworks and mechanisms for DF deployment.<br><br>Educate stakeholders. | Develop metrics and carry out implementation. | Evaluate and refine mechanisms and metrics as appropriate. |

**RECOMMENDATION 4**

## Comprehensively Incorporate Demand-Side Resources into Utility Resource Planning

### Overview

**Objective:** Ensure that the full value of demand-side resources is accounted for when making planning and resource investment decisions.

Utilities perform electricity planning to determine how to cost-effectively deploy grid resources that meet future demand growth and support system operations to maintain reliability. This recommendation applies to any activities oriented toward making investment decisions. Examples include integrated resource planning (IRP), transmission expansion planning, distribution resource planning, DER potential studies, DSM cost-effectiveness analysis, regulatory applications for DSM budgets, and resource adequacy studies. Utility planning often is bifurcated between distribution system planning activities and planning for the bulk system.[35] This only allows part of the demand side value proposition to be considered in any given planning decision. Integrating these disparate studies allows the value of EE and demand flexibility to be more fully represented.[36]

Utility planning activities often evaluate traditional infrastructure investment options in detail, but do not accurately account for the full value or performance characteristics of EE and demand flexibility measures. As a result, planning decisions can overlook demand-side opportunities that would otherwise reduce utility costs. To address this deficiency, system planners can identify, develop, and incorporate methods that more fully account for EE and demand flexibility into existing resource planning activities.

Modeling limitations are a key challenge, especially for accurately representing demand flexibility operations and value in resource planning relative to other resources. Many off-the-shelf resource planning models are not capable of capturing the locational and temporal value of demand flexibility resources. Options for addressing this challenge include transitioning to a more sophisticated planning model or analyzing demand flexibility measures through potential studies (or other such studies) that occur outside the resource planning model but allow for a greater degree of flexibility and nuance in analyzing demand flexibility measures.

### Key Actions

- **Ensure that a comprehensive list of demand-side measures is considered in the analysis.** Planning studies could extend beyond analysis of conventional DR to also include emerging options (e.g., grid-interactive water heating, bring-your-own-thermostat programs, EV managed charging).
- **Account for all applicable value streams.** As distributed resources, EE and demand flexibility can provide benefits that range from locational benefits on the distribution system to avoided costs on the bulk power system to environmental and "non-energy benefits" such as improved comfort or resilience.
- **Develop robust representation of demand flexibility measure performance characteristics.** Demand flexibility measures are unique in that their availability and dispatchability are constrained by the preferences and energy consumption behavior of the participating customers. Pilot results and simulations are useful resources for developing measure-specific performance parameters and assumptions, and ensuring a reasonable comparison between demand-side resources and other resources.

35 Vertically integrated utilities perform bulk system planning.

36 For example, a NARUC-NASEO taskforce has been assembled to align various electricity planning processes. See: https://www.naruc.org/taskforce/.

- **Account for interactions between demand-side resources.** As load characteristics and the resource mix changes over time, this will impact the system value of the resources. This interaction can be addressed by modeling demand-side resources dynamically within a resource planning model, or otherwise approximately accounting for these effects in a "static" analysis outside the modeling framework.

- **Increase consideration of Non-Wires Solutions (NWS).** Non-wires solutions include EE, demand flexibility, and distributed generation as alternatives in transmission and distribution grid planning. This can be effective in deferring the need for capital projects such as transmission lines or distribution substations.

- **Research and socialize best practices for incorporating demand-side resources into resource planning.**

### Portland General Electric's (PGE's) IRP

PGE has been implementing increasingly sophisticated approaches to representing demand flexibilitymeasures in its IRP. The past several cycles of IRP filings have reflected a growing "menu" of demand flexibility options, with the performance characterization of these resources being increasingly informed by the utility's growing base of demand flexibility pilots and demonstration projects. Additionally, the Oregon PUC requires PGE and the other regulated electric utilities to begin filing distribution resource system plans in October 2021.[36] PGE is establishing processes to leverage a common set of demand flexibility assumptions for both its IRP and its DRP. Much of the impetus for demand flexibility development has come from an institutional desire within the utility to use demand flexibility as an opportunity to engage with customers and provide new products and services.

### TIMING FOR RECOMMENDATION 4
**Comprehensively Incorporate Demand-Side Resources into Utility Resource Planning**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Develop analytical capabilities.<br><br>Incorporate into first planning cycle. | Refine and update DF modeling approaches.<br><br>Integrate bulk system and distribution planning practices. | Continued evelopment and refinement of capabilities. |

37 For more information, see: https://apps.puc.state.or.us/orders/2020ords/20-485.pdf.

PILLAR 3

# Empowering GEB Users, Installers, and Operators

Realizing the full GEB opportunity ultimately depends on building owners and electricity customers choosing to adopt efficient technologies with advanced control capabilities and subsequently participate in demand flexibility programs. Pillar 3 focuses on facilitating GEB adoption and use by developing a deeper understanding of consumer motivations to invest in these technologies, developing tools that co-optimize energy, non-energy, and financial benefits, and shifting workforce training to include smart technologies so building technologies can be installed, operated and maintained for optimal performance.

**RECOMMENDATION 1**

## Understand How Users Interact with GEBs and the Role of Technology

### Overview

**Objective:** Ensure that users find value in and optimally engage with GEB technologies with advanced control capabilities.

To maximize the successful delivery and adoption of GEBs, it is critical to empower all users and incorporate their perspectives into the design and delivery of technology and market offerings. User segmentation is needed as there is extreme heterogeneity across users. These users include residential and commercial building owners, managers, operators, and occupants, as well as technology and service providers, and the entities responsible for deploying demand flexibility opportunities to consumers. Complementing some of the steps and recommendations in Pillars 1 and 4, there is an opportunity to more deeply understand user preferences, experiences, perceptions, and motivations with respect to building energy, services, and load flexibility.

While user- and human-centered design approaches are often used for consumer goods – from software interfaces, to electronics, to furniture – they are less commonly employed in the domain of building energy and equipment. Similarly, in home automation, where such approaches can be more common, energy and load flexibility are not driving concerns. The industry will therefore benefit from more comprehensive incorporation of user-centric approaches to complement the technology- and policy-centric perspectives.

### Key Actions

- **Understand user perceptions of the value of providing demand flexibility.** To maximize customer desire for GEBs, third-party service offerings, program offerings, and technology capabilities must be grounded in the diversity of how building owners and occupants perceive the direct and societal benefits of grid-interactivity (or lack thereof) and their potential role in realizing and deriving value from these benefits. Users will have different motivations, concerns, and priorities that drive their relationship with and attitudes toward utilities, clean energy, technology, building operations.

- **Openly document technology installation, configuration, and operation experiences.** Building owners must manage several aspects related to technology interfaces, operation, and overall performance, including time, complexity, and cost. To increase satisfaction and reduce the "hassle factor" associated with realizing GEBs, industry and researchers would benefit from a collective set of lessons learned including both successes and failures.

- **Quantify user preferences for building service levels and availability.** For diverse types of end-use systems and building types, there is a need to understand the operational states and environmental conditions that will be satisfactory to users. Knowledge of the variables and measurement points to quantify these preferences and assess satisfaction can then be codified for inclusion in grid-interactive control logic and user-to-system feedback mechanisms.

- **Evaluate the relationship between prices, incentives, technologies, and load flexibility.** The extent to which prices and/or incentive levels drive load flexibility is connected to users' motivations, preferences, and end-use loads, and the capabilities of various technologies. Open questions include: how much does an increase in incentive (or price penalty) drive an increase in load flexibility, what are the limits of this effect, and how much do different types of incentives affect the consistency or reliability of response? Similarly, how do these issues vary by different technology, or by climate zone? Better understanding these factors will support the delivery of more effective and user acceptable GEBs.

### Portland General Electric Smart Grid Testbed

PGE's Smart Grid Testbed is exploring topics such as customer interest in new program offerings, and ways to leverage automation for customer convenience. Innovative program offerings include peak time rebates, EV smart charging, behind-the-meter battery storage, and smart water heating. A particular focus of the pilot is to determine the methods that are most effective for engaging various sub-segments of the population (e.g., messaging around bill savings and climate benefits of participation). The activities of the pilot are intended to provide "valuable insight into customer interactions with the programs and opportunities to demonstrate the benefits of adopting smart grid technologies at an unprecedented scale."

### TIMING FOR RECOMMENDATION 1
**Understand How Users Interact with GEBs and the Role of Technology**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Analyze user perceptions of DF value.<br><br>Document user experiences with technology.<br><br>Evaluate relationship between prices, incentives, technology and DF. | Quantify user preferences for building service levels. | Integrate lessons learned in DF technology and program design. |

## RECOMMENDATION 2
Develop Tools to Support Decision Making on Design and Operation of GEBs

### Overview

**Objective:** Ensure that utilities, design engineers, implementers, installers, aggregators, and building owners and operators can assess and select optimal portfolios of GEB technologies and strategies.

This recommendation applies to activities oriented toward making GEB technology investment and building operational decisions. The GEB value proposition is challenging to communicate to building owners and operators as benefits can vary significantly by building type, size, location, and electricity market. Decision support tools are needed to enable building owners and operators to identify the most relevant set of technologies for their specific situation. These tools can help users evaluate technology options along with energy, non-energy, and financial benefits for building owners and operators under a particular set of conditions. Decision support is needed to help various stakeholders including utilities, program administrators, and third-party aggregators identify the GEB technology packages that are most relevant for their particular markets.

While EE decision tools are well established, there are several challenges to expanding these tools to include demand flexibility, including: the need for hourly electric loads to appropriately represent shapes that vary by day of week, season, and climate, emissions profiles, digitalized control strategies, and accounting for diverse consumer preferences**.** GEB decision-making tools require reliable modeling of existing buildings based on real-world measurements. Yet, existing building operating data is imperfect or unavailable given limited sensors in buildings. For example, many residential and small and medium-sized commercial buildings do not sub-meter HVAC power, plug loads, and rooftop PVs, and lack sensors to estimate internal heat gain profiles. This lack of granular data hinders reliable building modeling for site-specific DR value propositions and advanced controls for GEBs. Further, comparing opportunities between EE, demand flexibility, PV, EV controls, and storage is extremely challenging because the order of strategy implementation is important, and each resource has different operating characteristics and limitations. Controls that can integrate the various resources are particularly challenging to model, not only for individual buildings, but also in cases where energy demand and storage should be optimized across multiple energy grids (e.g., heating network, electrical network, power to gas, combined heat and power, or electrical versus thermal storage).

### Key Actions

- **Enhance capabilities of existing building performance tools to include demand flexibility and GHG emissions information.** While there are several tools to help building owners and operators make cost-effective EE investments, many lack representations of demand flexibility technologies and strategies and/or DER characteristics. Further, there are limited publicly-available hourly greenhouse gas emissions profiles. For example, EE assessment tools that help provide initial screening of the value of various technologies for commercial and residential buildings such as Asset Score and Home Energy Score should be expanded to include demand flexibility and GHG assessment tools. These tools also need to be capable of modeling emerging technologies such as new forms of TES. Synergies with the existing building commissioning process can also be explored. Building commissioning is strongly recommended as a precursor to adding demand flexibility controls, to ensure that building operation is efficient and under control. A commissioning project may also be an ideal opportunity to assess the feasibility and potential benefits of adding demand flexibility strategies; doing so would require the development of new assessment protocols that could be integrated with the commissioning process.

- **Validate GEB modeling and decision support tools by comparing field data with simulation data.** Research is needed to compare simulated building load impacts with measured load impacts. Improving the predictive capabilities and precision of tools is critical to informed decision-making, as well as to drive further tool adoption.

- **Collect and publish data on the hard and soft costs of installing and configuring advanced sensing and control technologies needed for a fully optimized GEB and related DERs.** One significant challenge in modeling the value of GEB technologies is the lack of data on the cost to design, install, commission, and operate these technologies and systems. Cost data are needed on installation and commissioning in addition to hardware and other equipment costs.

- **Develop advanced data-driven analysis methods to support GEB technology decision support, design, and selection tools.** New data analytics methods such as machine learning can help integrate historical customer energy use patterns and related customer data with demand flexibility and DER retrofit designs. Such techniques can automate the identification of building characteristics such as size, type, usage patterns, vintage, and other physical attributes that most influence the value and selection of technologies that provide demand flexibility.

### TIMING FOR RECOMMENDATION 2

**Develop Tools to Support Decision Making on Design and Operation of GEBs**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Improve existing decision support and analysis tools to incorporate DF and DERs.<br><br>Enable GHG emissions analysis. | Develop decision and analysis tools using AI and ML analytics. | Deploy tools for all sectors and evaluate their use.<br><br>Maintain and support tools. |

**RECOMMENDATION 3**
## Integrate Education and Training on Advanced Building Technologies and Operations into Existing Building-Related Workforce Training Programs

### Overview

**Objective:** Incorporate advanced technology training as a subset of the building-related workforce education and training curricula for optimal building performance.

A skilled and experienced workforce is needed to support widespread GEB adoption. This recommendation applies to organizations involved in education and training for energy-related jobs, as well as jobs related to the design, construction, and operation of buildings.[38] Currently a knowledge gap exists related to the advanced controls, increased automation, and systems integration that are a key aspect of GEBs. Training programs and certifications on the design, construction, and operation of systems with advanced building technologies are needed for ongoing education of professionals, as well as for people entering this sector. Coordinating awareness, education, training, and recruitment among various fragmented, local stakeholder groups can be challenging. Clear communication between stakeholders (potentially through an intermediary) and publicly-available educational content could streamline this process and help advance the development of programs across the country.

Women, minorities, and workers from historically marginalized backgrounds are traditionally underrepresented in the EE sector. Ensuring more equitable representation may include steps such as: dedicating funding towards targeted outreach and education efforts to engage underrepresented workers, hiring locally, and implementing and enforcing policies with specific diversity goals.[39] In addition, as the energy workforce ages, timely and proactive recruitment efforts become essential. Educational outreach and engagement could help acquire new talent, mitigating these effects.

### Key Actions

- **Establish skill and credential standards relevant to advanced building technologies and operations.** A clearly defined set of baseline skills and standards helps both prospective employees and building professionals already in the workforce tailor their training.[40]

- **Expand relevant curricula, training programs, and certifications.** Education and training on advanced building technologies can be built into the curricula of various workforce development activities related to GEBs. The federal government may consider establishing national guidelines for required qualifications and potential certifications and trainings to promote consistency and quality of the buildings-related workforce.[41]

- **Broaden relevant workforce development programs.** A practical and efficient option is to expand relevant existing programs to include training

38 These organizations include, but are not limited to: community-based and not-for-profit organizations; technical high schools, community colleges, and universities; EE and clean technology businesses; trade associations; manufacturers; and unions.

39 This recommendation should be applied in consistence with existing local laws and regulations.

40 Skills may include operations and maintenance of smart buildings, system integration, system testing and evaluation, data acquisition and analysis, and system design and modeling. Funded by the Building Technologies Office, the Interstate Renewable Energy Council is developing a National Energy Efficiency Career Map, featuring skills and requirements for different job types. A similar map can be developed specifically for demand flexibility.

41 In addition, there is also a role for professional societies and associations such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the Illuminating Engineering Society (IES), and others that offer trainings and credentials.

on advanced building technologies, including DERs. This training should include information on the effect of advanced building technologies on building design, construction, operation, and maintenance.

- **Develop resources and provide funding to facilitate outreach to students in K-12 schools, community colleges, and universities.** Outreach to students can increase awareness and interest in the construction, operation, and maintenance of GEBs, helping to build the talent pipeline for the future. Outreach initiatives should also involve educators and guidance counselors, who can learn about career opportunities and key skills required in the industry.

- **Establish building training and assessment centers.** State or regional training centers with a focus on advanced technologies in buildings can develop resources for these workforce development efforts, help coordinate trainings, and share best practices. These training centers can partner with local colleges and universities for wider reach.

### The Pacific Gas and Electric Company

The Pacific Gas and Electric Company and Southern California Edison support the California Advanced Lighting Controls Training Program (CALCTP), a statewide initiative that aims to increase the use of lighting controls in commercial buildings. CALCTP features two training components: a technical program with lecture and laboratory instruction on the proper installation, programming, and maintenance of lighting control systems, as well as an acceptance-test technician program. The California utilities require their contractors to be CALCTP-certified, and they offer rebates for customers using CALCTP-certified contractors. CALCTP and similar training programs could be expanded to cover other grid-interactive and advanced building technologies.

### TIMING FOR RECOMMENDATION 3

**Integrate education and training on advanced building technologies and operations into existing building-related workforce training programs**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Establish skills and standards and expand training programs to cover DF technologies.<br><br>Assessing the status of existing workforce programs to meet necessary skills/ competencies. | Broaden workforce development programs and increase outreach.<br><br>Establish training centers. | Evaluate training programs and outreach for updates as technologies and needs change. |

PILLAR 4

# Supporting GEB Deployment Through Federal, State, and Local Enabling Programs and Policies

Effectuating change in the electricity sector often requires governmental support and policy intervention. Specifically, demand flexibility is a significant opportunity to meet renewable and decarbonization goals, and to do so affordably and effectively. Pillar 4 focuses on four areas for state and federal policy and program development that could help accelerate GEB deployment: "leading by example" with government buildings, expanding funding and financing options, codes and standards, and establishing goals, targets, or mandates related to resource procurement.

## RECOMMENDATION 1
## Lead by Example

### Overview

**Objective:** Develop initiatives for public buildings that demonstrate the substantial savings on electricity bills, reduction in carbon footprint, and resilience benefits for highly efficient and demand-flexible buildings, and provide data and insights about the costs, challenges, and benefits of advancing energy efficiency and demand flexibility.

Governments can advance energy efficiency and demand flexibility by incorporating GEB technologies and practices into buildings they own or operate; this can help raise public awareness of these solutions, and thus "lead by example." Such initiatives cover a wide range of activities and historically have focused on energy efficiency activities, including benchmarking building electricity consumption and demand, energy savings performance contracting (ESPC), and meeting sustainable building standards (e.g., LEED, Energy Star). Several of the recommendations in other Pillars could be applied to government buildings (e.g., developing building performance standards specifically for public buildings).

Undertaking the action steps under this recommendation will help demonstrate the full value of GEBs, for example, by showing substantial savings on electricity bills and reducing the carbon footprint for applicable buildings. A number of challenges may hinder progress including existing building manager education, limited performance data on GEBs to support quantitative policy actions, and limited financial incentives.

### Key Actions

As of September 2020, 47 states and the District of Columbia have established energy reduction or energy efficiency requirements that apply to government owned or maintained buildings. Most were established by executive order. Yet, none of these policies directly mandate demand flexibility. The following list provides options for policymakers to consider when establishing lead-by-example initiatives or adding demand flexibility provisions to existing initiatives. These options can be implemented through voluntary participation, executive order, legislation, or administrative rulemaking.

- **Promote demand flexibility for ESPC.** ESPC could include an additional emphasis on demand savings (kilowatts) from energy efficiency and demand flexibility, going beyond the current focus on energy savings (kilowatt-hours) and non-energy benefits like maintenance, or could include mandatory participation in demand flexibility and/or DR programs. ESPC contracts could include performance incentives that are tied to demand flexibility deployment, carbon intensity goals, or increasing on-site consumption of behind-the-meter renewable generation output.

- **Participate in DR and EE programs and markets.** Government-owned and operated facilities can participate in DR and EE programs directly through their electric utility or in centrally-organized wholesale electricity markets, typically through an aggregator. For example, in Massachusetts, the Division of Capital Asset Management and Maintenance has a contract with an aggregator to allow state, local, or quasi-governmental buildings to participate in ISO-New England's DR offerings.[42]

- **Broaden building energy tracking requirements in public buildings.** Lead by example policies often require building owners or operators to report energy consumption and energy use intensity. Reporting requirements could include reporting on:
  - Adoption of measures that promote demand flexibility;
  - Monthly peak demand (kW), including the hours during which the peak demand charges apply; and
  - The timing and duration of load reductions or increases.

### Potential GEB Benefits in U.S. General Services Administration (GSA) Buildings

Across the office portfolio of the U.S. General Services Administration (GSA), a recent study found that GEB measures could lead to 165 MW of peak load reduction and 180 GWh of reduction in annual energy consumption.[42] By investing in GEB measures, the GSA could generate $50 million in annual cost savings with a payback period of less than four years. The benefits to building owners are primarily due to lower electricity bills by reducing the demand- and energy-related portions of the bill (through energy efficiency measures and through load shifting if enrolled in time-varying pricing programs); and incentives and rebates to help offset the first cost of GEB investments. Building owners can also earn revenue by participating in DR programs. In addition, GEB measures can help enhance building control, leading to lower operations and maintenance costs, as well as increased occupant comfort.

### TIMING FOR RECOMMENDATION 1
**Lead by example**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Participate in EE and DR programs and markets.<br><br>Broaden building energy tracking reuirements. | Evaluate DF programs and initiatives and revise as needed. | Evaluate DF programs and initiatives and revise as needed. |

42 See: https://www.mass.gov/doc/fac89-designated-dcamm-contract-user-guide/download.

43 Matt Jungclaus, Cara Carmichael, and Phil Keuhn. "Value Potential for Grid-Interactive Efficient Buildings in the GSA Portfolio: A Cost-Benefit Analysis." Rocky Mountain Institute. 2019. http://www.rmi.org/GEBs_report

## RECOMMENDATION 2
## Expand Funding and Financing Options for GEB Technologies

### Overview

**Objective:** Identify and pursue effective financing and funding mechanisms that enable GEB technologies to be installed and/or used in buildings.

Funding and financing options for clean energy technologies can mitigate the upfront costs, which is a well-known barrier to adoption, and enable customers to unlock the positive lifetime savings from clean energy adoption. Federal and state governments often provide financial support for clean energy technologies throughout the supply chain to achieve certain policy goals, such as energy efficiency, emissions reductions, and job creation. Examples include high-efficiency heating and cooling systems, rooftop solar, and energy storage. Financing strategies include state revolving loan funds and green banks, as well as policies and programs that facilitate capital for energy savings performance contracting and utility-administered loans.[44] Funding support also includes tax incentives and rebates available after installation, as well as grants that provide funding prior to installation and upstream incentives to manufacturers and retailers that reduce retail prices for consumers.

Identifying and pursuing effective financing and funding mechanisms that enable GEB technologies to be installed and/or used in buildings can help accelerate the adoption of GEB technologies and increase the use of demand flexibility. It is important to consider both speed of distribution (e.g., tax incentives may be faster in reaching intended recipients than other vehicles) and incentive design (e.g., requirement to install vs. enroll in a demand flexibility program) when identifying the most promising financing or funding vehicles. It is also critical to identify how to assess performance. Specifically, M&V – including identification of actual results (metrics) and documentation of lessons learned – is critical to providing confidence that financing and funding mechanisms are achieving stated objectives. Note that GEB technologies are often less first-cost-intensive than other clean energy technologies; supportive financing, while valuable, may not be as acute as it is for other technologies.

### Key Actions

- **Evaluate financing and funding mechanisms and determine if new financial assistance mechanisms are needed.** If there are gaps that existing mechanisms cannot fill, determine what new financial assistance vehicles are needed to increase deployment of GEBs technologies.
- **Identify how requirements of existing financing and funding mechanisms for EE can be modified to include demand flexibility.** For example, programs that provide weatherization support for homes may examine including technologies that enable demand flexibility.
- **Promote partnerships between utilities and entities that work with underserved communities.** Coordination and partnership with publicly-funded programs, such as housing rehabilitation, can improve access to and participation in EE and demand flexibility programs, extending the reach of these programs to include underserved communities.

44 Green banks help secure low-cost capital for clean energy projects at favorable rates and terms through credit enhancements, aggregation of loans, technical assistance, and co-investment with private capital. Other notable funding alternatives include EE mortgages, credit enhancement for loans, on-bill financing and repayment, Property Assessed Clean Energy, or PACE.

### Federal Energy Efficiency Tax Credit

The U.S. government provides a number of federal income tax credits for energy efficiency. For example, homeowners can earn a tax credit of 10% of the cost up to $500 (or a specific amount from $50 to $300) for qualified energy efficiency improvements, including insulation products, roofs with materials that reduce heat gain, and energy-efficient windows, doors, and skylights.[44] In order to qualify, products such as roofs and windows must be ENERGY STAR-certified. A similar tax credit structure is available for the purchase of qualified appliances such as air-source heat pumps, central air conditioning, water boilers, furnaces, and water heaters.[45] Builders of new energy-efficient homes (defined as homes with 50% energy savings for heating and cooling over the 2006 International Energy Conservation Code) are also eligible for a tax credit of up to $2,000.[46]

#### TIMING FOR RECOMMENDATION 2
**Expand funding and financing options for GEB technologies**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Modify existing financial assistance mechanisms to include DF measures.<br><br>Initiate establishment of new funding mechanisms. | Distribute funds through modified existing and new mechanisms and evaluate effectiveness. | Make revisions to financing and funding mechanisms to accomodate new technologies and strategies and market developments. |

45 26 USC § 25C. See also https://www.energystar.gov/about/federal_tax_credits/non_business_energy_property_tax_credits

46 Ibid.

47 26 USC § 45L. See also https://www.energystar.gov/about/federal_tax_credits/federal_tax_credit_archives/tax_credits_home_builders

## RECOMMENDATION 3
## Expand Codes and Standards to Incorporate Demand Flexibility

### Overview

**Objective:** Determine the type of policy actions on codes and standards that will support demand flexibility deployment, and provide such information to policymakers at all levels of government.

Regulatory measures provide a way for the government to establish the bounds of a market and protect consumers. Within the building energy sector, there are a variety of regulatory tools that span different aspects of the building and different levels of government (i.e., federal, state, and local).[48] It should be noted that these types of regulatory measures are typically employed once a technology or economic sector is mature. GEBs as a field is still nascent, but assessing regulatory options now will help ensure that impactful regulations are enacted in the future.

State and local building energy codes reduce energy use in new buildings and major renovations by establishing minimum EE requirements for building design, construction, and remodeling. They are typically based on model energy codes developed by the International Code Council and ASHRAE. Some jurisdictions (e.g., Washington state and several cities) have adopted building performance standards that require existing buildings to meet a performance benchmark, such as an energy or carbon intensity metric, over time. In general, codes and standards similar to these can lead to large energy savings.

Development, adoption, and enforcement of energy codes and minimum EE standards at the local, state, and federal level could be used to help make demand flexibility common in buildings. Energy codes and standards are designed to be cost-effective, with operational savings expected to offset capital costs. However, the combination of higher upfront costs and uncertain/unquantifiable benefits complicates the establishment of codes or standards that require demand flexibility in addition to EE.

### Key Actions

These steps can be applied across building code or efficiency standards:

- **Determine aspects of demand flexibility that may be considered for codification.** Capabilities to enhance demand flexibility are in various stages of development and deployment, with different value propositions and tradeoffs. An assessment of the readiness level of various grid-interactive elements helps build a benefit case for what should be codified. This activity could be coupled with research to determine the basic elements of codes and standards that would have the greatest impact on increasing demand flexibility in buildings.
- **Combine grid-interactive requirements and open standards for automated communication with EE requirements.** This should include the use of open standards for communication and automation to improve interoperability in these technologies.
- **Provide technical assistance to government entities and professional organizations responsible for codes and standards development.** Such assistance could support education and training on load flexibility and related codes and standards.

48 DOE sets and periodically reviews minimum EE standards for common appliances and equipment used in buildings. States can set EE standards for products sold or installed in their state where federal standards are not in place. Many products now covered by national EE standards were first subject to state standards

### California Title 24 and SB 49

As part of the California Building Standards Code (Title 24), the California Energy Commission (CEC) developed requirements for buildings to install DR automation technology. Under the new requirements, thermostats, HVAC systems, networked lighting controllers, BASs must have two-way communication and be demand responsive using OpenADR, a common open industry led standard. Requiring these grid-interactive features and functionality in new buildings will reduce the cost for automated DR and enable buildings to operate more flexibly in the future. More recently, California passed a bill that requires the CEC to adopt and update standards for appliances in order to facilitate the deployment of demand flexibility technologies.[48] The CEC will also consider how such appliance standards can be aligned with existing DR programs in the state.

**TIMING FOR RECOMMENDATION 3**

**Expand Codes and Standards to Incorporate Demand Flexibility**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Determine aspects of DF/GEB ready to be codified.<br><br>Incorporate DF provisions in codes and standards.<br><br>Identify opportunities to link funding and programs to DF code actions. | Provide new funding for state and local governments to update DF provisions in cods & standards. | Evaluate, refine, and update codes and standards as appropriate. |

49 California Senate Bill No. 49: https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201920200SB49.

## RECOMMENDATION 4
## Consider Implementing Demand Flexibility in State Targets or Mandates

### Overview

**Objective:** Develop and implement policies that would require increased demand flexibility deployment over time, or establish goals and targets for doing so.

Policymakers and regulators often establish targets or mandates for resource procurement for utilities and other covered entities. Examples include renewable portfolio standards, which require that a specified share of energy (or capacity) be produced from qualifying renewable energy generation, typically increasing over time; clean energy standards, a policy option for increasing the role of zero or low-carbon generation sources; and EE resource standards, which require utilities to achieve a certain percentage of energy savings based on the amount of electricity (or natural gas) sold in the state, and storage procurement and peak demand reduction mandates. A similar concept could be extended to demand flexibility, with legislation or regulatory commissions including demand flexibility requirements, targets, or goals as part of these standards, or establishing discrete demand flexibility deployment requirements. Assessment practices for measuring and verifying the performance of demand flexibility resources is important for documenting the impacts of demand flexibility requirements. For targets or mandates to be effective, they must be enforced, and mitigation plans may be needed if the goals are not met.

### Key Actions

- **Conduct research to assess cost-effective and achievable demand flexibility potential for a given jurisdiction or service territory.**

- **Consider implementing peak reduction standards.** Much of the value of demand flexibility is in its ability to reduce peak demand. Some states already include peak demand reduction requirements in their EE resource standards.

- **Consider establishing statewide or utility-specific demand flexibility procurement requirements.** Recent DF procurement requirements established by state regulatory commissions in Oregon[50] and Minnesota[51] are two examples.

50 The Oregon PUC required PGE to develop at least 77 MW of new winter DR resource and 69 MW of summer DR. The requirement was developed in the context of PGE's 2016 IRP and is discussed in its 2020 Flexible Load Plan filing.

51 The Minnesota PUC recently required that Xcel Energy develop 400 MW of new DR capability, and explore the potential for up to 1,000 MW of new DR additions. Further details are discussed in Xcel Energy's 2019 IRP.

### Massachusetts Clean Peak Energy Standard[51]

The Clean Peak Energy Standard requires retail electricity providers to meet a portion of peak period load with qualifying clean resources, including reductions in load. The standard focuses on periods of 1 to 4 hours when electricity demand net of renewables output is highest on the power system. The requirement escalates annually by 1.5% per year, starting in 2020 and reaching 16.5% by 2030. Demand flexibility is a qualifying resource, including resources such as energy storage and solar PV, among others.

### TIMING FOR RECOMMENDATION 4

**Consider Implementing Demand Flexibility in State Targets or Mandates**

| Near Term (0–2 years) | Medium Term (2–5 years) | Long Term (5–10 years) |
|---|---|---|
| Information gathering (if needed).<br>Introduce state goals.<br>Develop legislation or regulatory requirements. | Implement requirements.<br>Monitor for compliance. | Ongoing monitoring.<br>Update legislation or regulations as needed. |

52 For further detail, see: https://www.mass.gov/clean-peak-energy-standard.https://www.mass.gov/clean-peak-energy-standard.

# 6. Putting the Recommendations into Action

## Stakeholder Roles

The *National Roadmap for GEBs* provides a series of recommendations for a range of market and policy actors. All of these stakeholders, including customers, can – and hopefully will – play an important role in successfully implementing these recommendations. In doing so they will boost the American energy economy, improve environmental quality, and help the buildings sector realize the myriad benefits of making the built environment more grid-interactive and efficient. Each of these recommendations will require a coordinated effort across several diverse stakeholder groups. **FIGURE 13** identifies the stakeholders with responsibility to successfully implement each recommendation. The figure is a strict summary of the stakeholders for which "key actions" were identified in Chapter 5 of the *Roadmap*. There could be additional, meaningful implementation roles for stakeholders not reflected in this figure.

More than 100 practitioners, researchers, regulators, policymakers, and other experts contributed to developing and writing this *Roadmap*. The recommendations, however, are put forward by DOE's Building Technologies Office (BTO), who authorized the *Roadmap*. BTO will continue to play a major role in advancing the recommendations, but certainly cannot succeed without the active involvement and collaboration of the other stakeholders and ultimately, energy and building decision-makers and customers.

## The Need for Leadership

Grid-interactive efficient buildings – and the associated improvements in demand flexibility – are being increasingly valued as essential elements of climate change mitigation and a growing clean energy economy. Unfortunately, GEBs and the policies and programs to support them have not yet grown commensurately. Strong leadership that works effectively across all key market actors, policy and program actors, and other stakeholder groups is necessary to successfully realize this enormous opportunity. Ideally such leadership will implement the *Roadmap's* recommendations, and in a forward-looking, innovative, assertive, and stakeholder-friendly manner that maximizes the benefits and successfully navigates challenges as they arise.

EE and demand flexibility have long benefited from strong leadership from federal, state, industry, and other officials, as can GEBs. Two recent examples of state-level leadership on GEBs: the Minnesota Public Utilities Commission (PUC) mandated utility demand flexibility procurement, which resulted in Xcel Energy pursuing 400 MW of new DR capability as an addition to an already extensive DR portfolio. Also, Portland General Electric has developed innovative new demand flexibility programs due to an executive-level focus on engaging its Oregon customers. Other examples of strong and forward-looking leadership among federal government, state government, and utilities are discussed throughout this report.

GEB champions are needed among consumers and other energy decision-makers as well. Particularly within large commercial buildings, several individuals – including building owners, facilities managers, and tenants – may be involved in the decision to invest in GEB technologies and to operate them properly. As with other building and energy management issues, a champion internal to an organization who understands GEBs' opportunities and can articulate the benefits will be instrumental in promoting technology adoption within the organization and its buildings.

## DOE's Role in Advancing GEBs

Given its national scope, resources, legal authorities, convening power, and new commitment to forceful measures to mitigate $CO_2$ emissions, DOE can – and needs to – play a central role in advancing GEBs as a resource for the future U.S. clean energy economy and modern electric grid, and relatedly in advancing grid-interactivity and efficiency as a resource to make the nation's homes and buildings more affordable and sustainable.

Based on the enormous opportunity identified in this *Roadmap*, DOE is establishing a national goal of **tripling the energy efficiency and demand flexibility of buildings by 2030 relative to 2020 levels**, helping to increase the reliability, resiliency, and flexibility needed to support a clean electricity grid. Energy efficiency and demand flexibility can be provided and procured through a variety of avenues. However, this GEB *Roadmap* goal is based on detailed analysis of achievable potential impacts in utility-administered EE and load flexibility programs, relative to 2019 reported levels.[53]

With respect to advancing GEBs, DOE – and its Building Technologies Office – has many valuable roles, as outlined in Chapter 5 of this *Roadmap*. BTO, with its partners, has invested considerable financial, intellectual, and other resources to support the development, deployment, and adoption of GEBs and will continue to aggressively maintain its roles and responsibilities in this arena. Other offices within DOE and elsewhere in the U.S. Government will also provide very substantial GEB-related commitments and resources, particularly as those offices strive to meet new climate, economic, and building sector goals.

Beyond such direct actions, BTO and other DOE offices can foster the development of champions and leaders throughout the GEB-related ecosystem. Opportunities include:

**Expand GEB potential analysis with DER integration and other considerations, and broadly communicate the associated benefits.** Chapter 2 of this *Roadmap* quantifies significant power system benefits associated with widespread but achievable levels of GEB adoption: $100 billion to $200 billion in cost savings through 2040 and a 6% reduction in U.S. power sector $CO_2$ emissions. The benefits must be widely communicated in order to motivate decision-makers to act on GEB deployment. Additional analysis of GEB benefits could provide further nuances, such as exploring customer bill impacts or distribution system benefits. The additional benefits of coordinated deployment of building-integrated DERs will improve the GEB value proposition. An important next phase of the analysis would extend to include other DERs such as electric vehicles, energy storage, and distributed generation.

**Convene GEB events with a focus on consumers.** DOE has the ability to convene diverse groups of stakeholders, both regionally and nationally. While there are organizations that do this, the *Roadmap* identified a need to focus more specifically on consumers. Events that are geared specifically toward the issues facing building owners and managers, as well as consumer organizations, will increase awareness

53 These results are measured on annual basis by EIA-861 and reported in Table 10.6 Energy Savings "Incremental Annual Savings - Energy Savings (MWh)" and Table 10.8 Demand Response "Actual Peak Demand Savings (MW)" for the commercial and residential sectors.

among potential GEB technology adopters.

**Initiate a national awareness and communications campaign.** DOE could establish a framework for communicating the benefits and opportunities of GEBs to stakeholders at a national and local level, with a particular focus on communications with consumers. FERC's *National Action Plan for Demand Response*[54] successfully communicated DR potential and actionable steps, and the themes of that report could be repurposed here with a broader focus on GEBs. Key elements of a communications plan could include, for example, conducting foundational market research, developing communications materials and toolkits, and supporting local efforts to increase awareness of GEB opportunities.

**Increase state technical assistance on EE and DF-related topics.** Regulators need dependable and unbiased information upon which to establish EE and demand flexibility initiatives and rulings. DOE has a long history of supporting state technical assistance through stakeholder workshops, trainings, and state-specific analytical research. State technical assistance also could focus on other key issues that are of interest to regulators, such as options for making GEB benefits accessible to underserved communities, maximizing the consumer benefits of GEBs, or improving assessment of GEB performance through enhanced M&V practices.

54 FERC Staff, "National Assessment and Action on Demand Response," prepared with the support of The Brattle Group, GMMB, Customer Performance Group, Definitive Insights, and Eastern Research Group, June 17, 2010. For more information, see: https://www.ferc.gov/electric/industry-activity/demand-response/national-assessment-and-action-plan-demand-response.

| Recommendation | GOVERNMENT | | | | | |
|---|---|---|---|---|---|---|
| | DOE Building Technologies Office | Federal Government | Utility Regulator | State/Local Government | Utility | Market Operator |
| **Pillar 1: Advancing GEBs Through Research, Development, and Data** | | | | | | |
| Develop/accelerate deployment of GEB technologies | ✓ | ✓ | | ✓ | ✓ | |
| Accelerate technology interoperability | ✓ | ✓ | ✓ | | ✓ | |
| Improve access and use of DF data | ✓ | ✓ | ✓ | ✓ | ✓ | ✓ |
| **Pillar 2: Enhancing the Value of GEBs to Consumers and Utilities** | | | | | | |
| Develop innovative incentive-based programs | ✓ | ✓ | ✓ | ✓ | ✓ | |
| Expand price-based program adoption | | | ✓ | | ✓ | |
| Introduce incentives for utilities to deploy demand-side resources | | ✓ | ✓ | | ✓ | ✓ |
| Incorporate DF into resource planning | | ✓ | ✓ | | ✓ | ✓ |
| **Pillar 3: Empowering GEB Users, Installers, and Operators** | | | | | | |
| Understand user interactions with GEBs and role of technology | ✓ | | ✓ | | ✓ | |
| Develop GEB design & operation decision-making tools | ✓ | | ✓ | | ✓ | |
| Integrate smart technology training into existing programs | ✓ | ✓ | | ✓ | ✓ | |
| **Pillar 4: Supporting GEB Deployment Through Federal, State, and Local Enabling Programs and Policies** | | | | | | |
| Lead by example | ✓ | ✓ | | ✓ | ✓ | |
| Expand funding and financing options | ✓ | ✓ | | ✓ | | |
| Consider use of codes & standards | ✓ | ✓ | | ✓ | | |
| Consider implementing state targets/mandates | | | ✓ | ✓ | ✓ | |

**FIGURE 12: STAKEHOLDER INVOLVEMENT IN IMPLEMENTING THE ROADMAP RECOMMENDATIONS**

| Recommendation | IMPLEMENTER | | RESEARCHER | | | |
|---|---|---|---|---|---|---|
| | Aggregator/ ESCO | Implementation Support | Researcher/ Labs | Policy Advocacy | Technology Developer | Other (see notes) |
| **Pillar 1: Advancing GEBs Through Research, Development, and Data** | | | | | | |
| Develop/accelerate deployment of GEB technologies | ✓ | | ✓ | | ✓ | |
| Accelerate technology interoperability | ✓ | ✓ | ✓ | | ✓ | ✓ |
| Improve access and use of DF data | ✓ | ✓ | ✓ | ✓ | ✓ | |
| **Pillar 2: Enhancing the Value of GEBs to Consumers and Utilities** | | | | | | |
| Develop innovative incentive-based programs | ✓ | | ✓ | | | |
| Expand price-based program adoption | | | | ✓ | | |
| Introduce incentives for utilities to deploy demand-side resources | ✓ | | | | | ✓ |
| Incorporate DF into resource planning | | | ✓ | | | |
| **Pillar 3: Empowering GEB Users, Installers, and Operators** | | | | | | |
| Understand user interactions with GEBs and role of technology | ✓ | | ✓ | ✓ | ✓ | |
| Develop GEB design & operation decision-making tools | ✓ | ✓ | ✓ | | ✓ | |
| Integrate smart technology training into existing programs | | | | | | ✓ |
| **Pillar 4: Supporting GEB Deployment Through Federal, State, and Local Enabling Programs and Policies** | | | | | | |
| Lead by example | ✓ | | | | | |
| Expand funding and financing options | | | | ✓ | | |
| Consider use of codes & standards | | | | | | |
| Consider implementing state targets/mandates | | | | ✓ | ✓ | |

**Notes on "Other" category:** Customers can help accelerate technology interoperability by ensuring that solutions are effective. Consumer advocates can provide insights into impacts of new incentive mechanisms on customers. Educational institutions and workforce development boards will have a key role in implementing aspects of the recommendation to integrate smart technology training into existing programs.

# References

## Further Reading for the Recommendations

### Pillar 1: Advancing GEBs Through Research, Development, and Data

#### Recommendation 1: Research, Develop, and Accelerate Deployment of GEB Technologies


- Battelle Memorial Institute. "Pacific Northwest Smart Grid Demonstration Project Technology Performance Report." Battelle Memorial Institute, Pacific Northwest Division, June 2015.
- Drgoňa, Ján, Javier Arroyo, Iago Cupeiro Figueroa, David Blum, Krzysztof Arendt, Donghun Kim, Enric Perarnau Ollé, Juraj Oravec, Michael Wetter, Draguna L. Vrabie, and Lieve Helsen. "All you need to know about model predictive control for buildings." Annual Reviews in Control, September 2020.
- Kaur, Sumanjeet, Marcus Bianchi, and Nelson James. "2019 Workshop on Fundamental Needs for Dynamic and Interactive Thermal Storage Solutions for Buildings." National Renewable Energy Laboratory, June 2020.
- Kohlhepp, Peter, Hassan Harb, Henryk Wolisz, Simon Waczowicz, Dirk Müller, and Veit Hagenmeyer. "Large-scale grid integration of residential thermal energy storages as demand-side flexibility resource: A review of international field studies." Renewable and Sustainable Energy Reviews, March 2019.
- Lawrence Berkeley National Laboratory: Energy Management and Information Systems.
- National Renewable Energy Laboratory: NREL's Home Energy Management System—foresee.
- Regnier, Cindy, Paul Mathew, Alastair Robinson, Jordan Shackelford, and Travis Walter. "Systems Retrofit Trends in Commercial Buildings: Opening Up Opportunities for Deeper Savings." Lawrence Berkeley National Laboratory, February 2020.

### Recommendation 2: Accelerate Technology Interoperability to Optimize Efficiency and Demand Flexibility Performance


- ASHRAE (2018). ASHRAE Standard Committee 223p.
- Balaji, Bharathan, Arka Bhattacharya, Gabriel Fierro, Jingkun Gao, Joshua Gluck, Dezhi Hong, et al. "Brick: Towards a unified metadata schema for buildings." BuildSys '16: Proceedings of the 3rd ACM International Conference on Systems for Energy-Efficient Built Environments, November 2016.
- Bergmann, Harry, Cory Mosiman, Avijit Saha, Selam Haile, William Livingood, Steven Bushby, Gabe Fierro, Joel Bender, Michael Poplawski, Jessica Granderson, and Marco Pritoni. "Semantic Interoperability to Enable Smart, Grid-Interactive Efficient Buildings." 2020 ACEEE Summer Study on Energy Efficiency in Buildings, August 2020.
- Brick: Brick Schema.
- CHIP: Project Connected Home over IP.
- Fierro, Gabe, Anand Prakash, Cory Mosiman, Marco Pritoni, Paul Raftery, Michael Wetter, and David Culler. "Shepherding Metadata Through the Building Lifecycle." BuildSys '20: Proceedings of the 7th ACM International Conference on Systems for Energy-Efficient Buildings, Cities, and Transportation, November 2020.
- Gaidon, Clement and Poplawski, Michael. "Connected Lighting System Interoperability Study Part 1: Application Programming Interfaces." Pacific Northwest National Laboratory, October 2017.


### Recommendation 3: Collect and Provide Data and Develop Analytical Methods for Benchmarking and Evaluating Demand Flexibility Technology and Whole Building GEB Performance


- Bonneville Power Administration. Estimating Peak Demand Impacts Application Guide Version 1.0. June 2019.
- Kisch, Teddy, Eric Rubin, Thomas Tu, Kelly Sanders, Jason Huffine, and Brittany Luntz. "Energy Savings from Networked Lighting Control Systems." DesignLights Consortium, September 2017.
- Liu, Jingjing, Rongxin Yin, Marco Pritoni, Mary Ann Piette, and Monica Neukomm. "Developing and Evaluating Metrics for Demand Flexibility in Buildings: Comparing Simulations and Field Data." 2020 ACEEE Summer Study on Energy Efficiency in Buildings, August 2020.
- Schwartz, Peter, Brian F Gerke, Jennifer Potter, Alastair Robinson, David Jagger, Kelly Sanders, Yao-Yung Wen, Jasmine Shepard, and Teddy Kisch. "The Value Proposition for Cost-Effective, Demand Responsive-Enabling, Nonresidential Lighting System Retrofits in California Buildings." Lawrence Berkeley National Laboratory, April 2019.
- Siemens: SureGrid Demand Response.

## Pillar 2: Enhancing the Value of GEBs to Consumers and Utilities

### Recommendation 1: Improve and Expand Innovative Customer Demand Flexibility Program Offerings

- Perry, Christopher, Hannah Bastian, and Dan York. "Grid-Interactive Efficient Building Utility Programs: State of the Market." An ACEEE whitepaper, October 2019.
- HECO.
- Satchwell, Andrew and Peter Cappers. "Evolving Grid Services, Products, and Market Opportunities for Regulated Electric Utilities." Lawrence Berkeley National Laboratory, May 2018.
- Schwartz, Lisa and Greg Leventis. "Grid-Interactive Efficient Buildings: An Introduction for State and Local Governments." State and Local Energy Efficiency Action Network, Lawrence Berkeley National Laboratory, April 2020.

### Recommendation 2: Expand Consumer Knowledge and Consideration of Price-Based Demand Flexibility Programs

- Faruqui, Ahmad, Sanem Sergici, and Cody Warner. "Arcturus 2.0: A Meta-Analysis of Time-Varying Rates for Electricity." *The Electricity Journal*, Volume 30, Issue 10, December 2017.
- Faruqui, Ahmad, Ryan Hledik, and Jenny Palmer. "Time-Varying and Dynamic Rate Design." Prepared for the Regulatory Assistance Project, July 2012.
- Glick, Devi, Matt Lehrman, and Owen Smith. "Rate Design for the Distribution Edge." Rocky Mountain Institute, August 2014.
- Satchwell, Andrew, Peter Cappers, and Galen Barbose. "Current Developments in Retail Rate Design: Implications for Solar and Other Distributed Energy Resources." Lawrence Berkeley National Laboratory, July 2019.
- U.S. DOE. Consumer Behavior Studies resources.

### Recommendation 3: Introduce Incentives for Utilities to Deploy Demand-Side Resources

- Goldenberg, Cara, Dan Cross-Call, Sherri Billimoria, and Oliver Tully. "PIMs for Progress: Using Performance Incentive Mechanisms to Accelerate Progress on Energy Policy Goals." Rocky Mountain Institute, 2020.
- Lowry, Mark and Tim Woolf. "Performance-Based Regulation in a High Distributed Energy Resources Future." Lawrence Berkeley National Laboratory, January 2016.
- Satchwell, Andrew, Peter Cappers, Lisa C. Schwartz, and Emily Martin Fadrhonc. "A Framework for Organizing Current and Future Electric Utility Regulatory and Business Models." Lawrence Berkeley National Laboratory, June 2015.
- Satchwell, Andrew and Peter Cappers. "Evolving Grid Services, Products, and Market Opportunities for Regulated Electric Utilities." Lawrence Berkeley National Laboratory, May 2018.

- Steven R. Schiller, Lisa Schwartz, and Sean Murphy. "Performance Assessments of Demand Flexibility from Grid-Interactive Efficient Buildings: Issues and Considerations." State and Local Energy Efficiency Action Network and Lawrence Berkeley National Laboratory, 2020.
- Zarakas, William, Toby Brown, Lea Grausz, Heidi Bishop, and Henna Trewn. "Performance Based Regulation Plans: Goals, Incentives and Alignment." Prepared for DTE Energy, December 2017.

### Recommendation 4: Comprehensively Incorporate Demand-Side Flexibility into Utility Resource Planning

- Eckman, Tom, Lisa C Schwartz, and Greg Leventis. "Determining Utility System Value of Demand Flexibility from Grid-interactive Efficient Buildings." Prepared for the State Energy Efficiency Action Network, April 2020.
- Electric Power Research Institute. "Incorporating Energy Efficiency and Demand Response into Electric Company Power System Resource Planning." Prepared by The Brattle Group, August 2020.
- Electric Power Research Institute. "The Total Value Test: A Framework for Evaluating the Cost-Effectiveness of Efficient Electrification." Prepared by The Brattle Group, August 2019.
- Mims Frick, Natalie and Lisa Schwartz. "Time-Sensitive Value of Efficiency: Use Cases in Electricity Sector Planning and Programs." Lawrence Berkeley National Laboratory, November 2019.
- National Energy Screening Project, "National Standard Practice Manual for Benefit-Cost Analysis of Distributed Energy Resources." August 2020.
- Satchwell, Andrew and Ryan Hledik. "Analytical Frameworks to Incorporate Demand Response in Long-Term Resource Planning." *Utilities Policy*, March 2014.

## Pillar 3: Empowering GEB Users, Installers, and Operators

### Recommendation 1: Understand How Users Interact with GEBs and the Role of Technology

- McGowan, Mary Kate. "ASHRAE Bacnet Committee Works with Other Organizations on New Standard." ASHRAE, March 2018.
- Meier, Alan, Therese Peffer, Marco Pritoni, and Cecilia Aragon. "Thermostat Interface and Usability: A Survey." Lawrence Berkeley National Laboratory, September 2010.
- Nordman, Bruce, Margarita Kloss, Bijit Kundu, et al. "Energy Reporting: Device Demonstration, Communication Protocols, and Codes and Standards." Lawrence Berkeley National Laboratory, 2019.
- Shen, Lester. "Human-Building Interaction: Design Thinking and Energy Efficiency." Center for Energy and Environment, May 2015.

## Recommendation 2: Develop Tools to Support Decision Making on Design and Operation of GEBs

- OpenBuildingControl.
- URBANopt: Urban Renewable Building and Neighborhood Optimization.
- Yin, Rongxin and Douglas Black. "Improvement of Demand Response Quick Assessment Tool (DRQAT) and Tool Validation Case Study." Lawrence Berkeley National Laboratory, August 2015. NOTE: The latest version of DRQAT is Version 4.0.0. Download here.
- Yin, Rongxin, Emre Kara, Yaping Li, Nicholas DeForest, Ke Wang, Taiyou Yong, and Michael Stadler. "Quantifying Flexibility of Commercial and Residential Loads for Demand Response Using Setpoint Changes." Applied Energy, vol. 177, September 2016.
- Yin, Rongxin, Peng Xu, Mary Ann Piette, Sila Kiliccote. "Study on Auto-DR and Pre-cooling of Commercial Buildings with Thermal Mass in California." Energy and Buildings, vol. 42(7), July 2010.

## Recommendation 3: Integrate Education and Training on Advanced Building Technologies and Operations into Existing Building-Related Workforce Training Programs

- ICLEI Local Governments for Sustainability and Institute for Market Transformation. "Green Workforce Development: Meeting and Driving Demand for Energy Efficiency Services."
- Interstate Renewable Energy Council, Solar Career Map. Accessed December 11, 2020.
- Peters, Jane, Nathaniel Albers, Charles A. Goldman, Elizabeth Stuart, and Merrian Fuller. "Energy Efficiency Services Sector: Workforce Education and Training." ACEEE Summer Study on Energy Efficiency in Buildings, 2010.
- Shoemaker, Mary and David Ribeiro. "Through the Local Government Lens: Developing the Energy Efficiency Workforce." ACEEE, 2018.
- Shoemaker, Mary and Roxana Ayala. "Cities and Clean Energy Workforce Development." ACEEE, 2020.
- Srivastava, Rohini, Mohammed Awojobi, and Jennifer Amann. "Training the Workforce for High-Performance Buildings: Enhancing Skills for Operations and Maintenance." ACEEE, September 2020.
- The Solar Foundation and The Solar Training Network. "Strategies for Solar Workforce Development."
- U.S. DOE. "Solar Training Network." Accessed December 11, 2020.

## Pillar 4: Supporting GEB Deployment Through Federal, State, and Local Enabling Programs and Policies


### Recommendation 1: Lead by Example

- Jungclaus, Matt, Cara Carmichael, and Phil Keuhn. "Value Potential for Grid-Interactive Efficient Buildings in the GSA Portfolio: A Cost-Benefit Analysis." Rocky Mountain Institute, 2019. http://www.rmi.org/GEBs_report.
- Energy Star. "Lead by Example." Accessed December 11, 2020.
- Environmental Protection Agency. "Lead by Example Guide: Clean Energy Strategies, Resources, and Action Steps for State Programs." June 2009.
- GSA Green Building Advisory Committee. "Advice Letter on Building & Grid Integration." December 13, 2018.
- NASEO. "Considerations for Grid-interactive Efficient Buildings (GEB) Pilot Projects." December 2019.
- U.S. General Services Administration. "About GSA's Proving Grounds (GPG)." Accessed December 11, 2020.

### Recommendation 2: Expand Funding and Financing Options for GEB Technologies

- Alliance to Save Energy. "Performance-based Utility Program Workshop."
- Electric Power Research Institute. "Methodological Approach for Estimating the Benefits and Costs of Smart Grid Demonstration Projects." January 2010.
- Deason, Jeff, Greg Leventis, Charles A. Goldman, and Juan Pablo Carvallo. "Energy Efficiency Program Financing: Where It Comes From, Where It Goes, and How It Gets There." Lawrence Berkeley National Laboratory, June 2016.
- Saul Rinaldi, Kara, Elizabeth Bunnen, and Sabine Rogers. "Residential Grid-Interactive Efficient Building Technology and Policy: Harnessing the Power of Homes for a Clean, Affordable, Resilient Grid of the Future." Prepared for NASEO, October 2019.
- Dutta, Projjal, Ralph DiNola, and Sonia Punjabi. "GSA Green Building Advisory Committee Federal Building & Grid Integration: Proposed Roadmap Advice Letter." Letter to Kevin Kampschroer, December 9, 2019.
- Schiller, Steven R., Lisa Schwartz, and Sean Murphy. "Performance Assessments of Demand Flexibility from Grid-Interactive Efficient Buildings: Issues and Considerations." State and Local Energy Efficiency Action Network, Lawrence Berkeley National Laboratory July 2020.

### Recommendation 3: Expand Codes and Standards to Incorporate Demand Flexibility

- National Association of State Energy Officials (NASEO). "Grid-interactive Efficient Buildings: State Briefing Paper." October 2019.
- Saul Rinaldi, Kara, Elizabeth Bunnen, and Sabine Rogers. "Residential Grid-Interactive Efficient Building Technology

and Policy: Harnessing the Power of Homes for a Clean, Affordable, Resilient Grid of the Future." Prepared for NASEO, October 2019.

- Schwartz, Lisa and Greg Leventis. "Grid-Interactive Efficient Buildings: An Introduction for State and Local Governments." State and Local Energy Efficiency Action Network, Lawrence Berkeley National Laboratory, April 2020

### Recommendation 4: Consider Implementing Demand Flexibility in State Targets or Mandates

- Eckman, Tom, Lisa Schwartz, and Greg Leventis. "Determining Utility System Value of Demand Flexibility From Grid-interactive Efficient Buildings." Lawrence Berkeley National Laboratory, April 2020.
- Mims Frick, Natalie and Lisa Schwartz. "Time-Sensitive Value of Efficiency: Use Cases in Electricity Sector Planning and Programs." Lawrence Berkeley National Laboratory, November 2019.
- Gold, Rachel, Annie Gilleo, and Weston Berg. "Next Generation Energy Efficiency Resource Standards." ACEEE Report, August 2019.
- MA DOER. "Clean Peak Energy Standard." Accessed December 11, 2020.
- Schiller, Steven, Lisa Schwartz, and Sean Murphy. "Performance Assessments of Demand Flexibility from Grid-Interactive Efficient Buildings: Issues and Considerations." Lawrence Berkeley National Laboratory, July 2020.

## Relevant DOE Publications

- Lawrence Berkeley National Laboratory. "A Conceptual Framework to Describe Energy Efficiency and Demand Response Interactions." Prepared by Andrew J. Satchwell, et al., July 2020.
- Lawrence Berkeley National Laboratory. "Time-Sensitive Value of Efficiency: Use Cases in Electricity Sector Planning and Programs." Prepared by Natalie Mims Frick and Lisa Schwartz, November 2019.
- NEEP. "Grid-Interactive Efficient Buildings (GEBs) Tri-Region Status Report." Prepared by Giselle Procaccianti, January 2020.
- NREL. "Connected Communities: A Multi-Building Energy Management Approach." Prepared by Victor Olgyay, Seth Coan, Brett Webster, and William Livingood, May 2020.
- Pacific Northwest National Laboratory. "Challenges and Opportunities to Secure Buildings from Cyber Threats." Prepared by Hayden Reeve, et al., March 2020.
- State and Local Energy Efficiency Action Network. "Performance Assessments of Demand Flexibility from Grid-Interactive Efficient Buildings: Issues and Considerations." Prepared by Steven R. Schiller, Lisa Schwartz, and Sean Murphy, Lawrence Berkeley National Laboratory, July 2020.

- State and Local Energy Efficiency Action Network. "Determining Utility System Value of Demand Flexibility from Grid-Interactive Efficient Buildings." Prepared by Tom Eckman, Lisa Schwartz, and Greg Leventis, Lawrence Berkeley National Laboratory, April 2020.
- State and Local Energy Efficiency Action Network. "Grid-Interactive Efficient Buildings: An Introduction for State and Local Governments." Prepared by Lisa Schwartz and Greg Leventis, Lawrence Berkeley National Laboratory, April 2020.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Whole-Building Controls, Sensors, Modeling, and Analytics." Prepared by Amir Roth, December 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration." Prepared by Bill Goetzler, Matt Guernsey, and Theo Kassuga, December 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Windows and Opaque Envelope." Prepared by Chioke Harris, December 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series: Overview of Research Challenges and Gaps." Prepared by Monica Neukomm, Valerie Nubbe, and Robert Fares, December 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Lighting and Electronics." Prepared by Valerie Nubbe and Mary Yamada, December 2019.
- U.S. DOE. "End-Use Load Profiles for the U.S. Building Stock." Prepared by Natalie Mims Frick, et al., November 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Fact Sheet." April 2019.

## Additional References Supporting Chapter 3 and Appendix E (GEB Vision)

- ACEEE. "State of the Market: Grid-Interactive Efficient Building Utility Programs." Prepared by Christopher Perry, Hannah Bastian, and Dan York, October 2019.
- Fairley, Peter. "800,000 Microinverters Remotely Retrofitted on Oahu—in One Day." ***IEEE Spectrum,*** February 5, 2015.
- Hviid, Jakob, and Mikkel Baun Kjorgaard. "The retail store as a smart grid ready building: Current practice and future potentials." In 2018 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2018 1–5. doi:10.1109/ISGT.2018.8403354.
- Kjaergaard, Mikkel Baun, Krzysztof Arendt, Anders Clausen, Aslak Johansen, Muhyiddine Jradi, Bo Norregaard Jorgensen, Peter Nelleman, Fisayo Caleb Sangogboye, Christian Veje, and Morten Gill Wollsen. "Demand response in commercial buildings with an Assessable impact on occupant comfort." In 2016 IEEE International Conference on Smart Grid Communications (SmartGridComm), 2016, 447–452. IEEE. ISBN: 978-1- 5090-4075-9. doi:10.1109/SmartGridComm.2016.7778802.

- Lawrence Berkeley National Laboratory. "A Primer on Organizational Use of Energy Management and Information Systems (EMIS), Better Buildings Alliance." U.S. DOE, 2015.
- Sanguinetti, A., Karlin, B., Ford, R., et al. "What's energy management got to do with it? Exploring the role of energy management in the smart home adoption process." Energy Efficiency, 11, 1897–1911, 2018.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Whole-Building Controls, Sensors, Modeling, and Analytics." Prepared by Amir Roth, December 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration." Prepared by Bill Goetzler, Matt Guernsey, and Theo Kassuga, December 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Windows and Opaque Envelope." Prepared by Chioke Harris, December 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series: Overview of Research Challenges and Gaps." Prepared by Monica Neukomm, Valerie Nubbe, and Robert Fares, December 2019.
- U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Lighting and Electronics." Prepared by Valerie Nubbe and Mary Yamada, December 2019.
- V. M. Tayur and R. Suchithra. "Review of interoperability approaches in application layer of Internet of Things." In 2017 International Conference on Innovative Mechanisms for Industry Applications (ICIMIA), Bangalore, 2017, pp. 322-326, doi: 10.1109/ICIMIA.2017.7975628.

# Appendix A: Glossary

**Aggregator:** Any marketer, broker, public agency, city, county, or special district that combines the loads of multiple end-use customers in negotiating the purchase of electricity, the transmission of electricity, and other related services for these customers.

**Ancillary services:** A variety of operations beyond generation and transmission that are required to maintain grid stability and security. These services generally include frequency control, spinning reserves, and operating reserves. Traditionally, ancillary services were provided by generators and other equipment (e.g., capacitors) on the utility system. However, the development of smart building technologies has broadened the types of equipment that can be used to provide ancillary services.

**Anisotropic:** A physical property of a material that allows it to change or assume different properties. Typically used as thermal anisotropy in the context of building technologies for improved thermal management in building envelopes by enabling preferential heat transfer in one direction compared to another.

**BACnet:** A data communication protocol which is a set of rules governing the exchange of data over a computer network for building automation and control networks.

Building automation system (BAS): An energy management system, usually with additional capabilities, relating to the overall operation of the building in which it is installed, such as equipment monitoring, protection of equipment against power failure, and building security.

**Congestion:** When the lowest-priced energy is prevented from flowing freely to a specific area on the grid because heavy electricity use is causing parts of the grid to operate near their limits.

**CTA-2045:** A Modular Communications Interface for Energy Management standard published by the Consumer Technology Association (CTA) and dual-listed by the American National Standards Institute (ANSI). The standard defines a physical interface, also referred to as a socket or port, with pins that carry digital information.

**Decoupling:** An adjustable price mechanism that breaks the link between the amount of energy sold and the actual (allowed) revenue collected by the utility.

**Demand flexibility:** Capability provided by DERs to reduce, shed, shift, modulate or generate electricity; energy flexibility and load flexibility are often used interchangeably with demand flexibility.

**Demand response (DR):** Change in the rate of electricity consumption in response to price signals or specific requests of a Utility.

**Demand-side management:** The modification of energy demand by customers through strategies, including EE, DR, distributed generation, energy storage, electric vehicles, and/or time-of-use pricing structures.

**Distributed energy resource (DER):** A resource sited close to customers that can provide all or some of their immediate power needs and/or can be used by the utility system to either reduce demand or provide supply to satisfy the energy, capacity, or ancillary service needs of the grid.

**Electric vehicle (EV):** A vehicle that operates solely on electricity and does not use an internal combustion motor.

**Electricity consumption:** The use of electricity as a source of heat or power.

**Electricity demand:** The requirement for electricity as an input to provide products and/or services.

**Energy efficiency (EE):** Ongoing reduction in energy use to provide the same or improved function.

**Energy service performance contracting (ESPC):** A contract between two or more parties where payment is based on achieving specified results, which are typically guaranteed reductions in energy consumption and/or operating costs. Payments are often based on the cost savings associated with the anticipated results.

**Energy services company (ESCO):** A firm that provides a range of EE and financing services and guarantees that specified results will be achieved under an energy performance contract.

**EnergyStar:** A program of the U.S. Environmental Protection Agency which identifies the most energy-efficient products, buildings, plants, and new homes – all based on the latest government-backed standards and verified by a rigorous third-party certification process.

**Extra Supervisory Control:** Extra supervisory control is a functionality that monitors and maximizes synergies between individual buildings for optimization of energy use across multiple buildings.

**Grid services:** Services that support the generation, transmission, and distribution of electricity. This report focuses on grid services that can be provided by grid-interactive efficient buildings.

**Grid-interactive efficient building (GEB):** An energy-efficient building that uses smart technologies and on-site DERs to provide demand flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences in a continuous and integrated way.

**Heating, ventilation, air conditioning (HVAC):** The equipment, distribution systems, and terminals that provide, either collectively or individually, the processes of heating, ventilating, or air conditioning to a building or portion of a building.

**Hypertext transfer protocol (HTTP):** A communication protocol that is used to deliver data (e.g., HTML files, image files, query results) on the World Wide Web.

**Impact evaluation:** A performance assessment of multiple buildings in a program or tariff to determine its impacts, such as energy or demand savings.

**Independent System Operator/Regional Transmission Organization (ISO/RTO):** An independent, federally regulated entity established to coordinate regional transmission in a non-discriminatory manner and ensure the safety and reliability of the electric system.

**Integrated distribution system planning:** An assessment of the physical and operational changes to the electric distribution system necessary to enable safe, reliable, and affordable service that satisfies customers' changing expectations and use of DERs, generally in coordination with resource and transmission planning.

Integrated distribution system planning includes stakeholder-informed planning scenarios to support a reliable, efficient, and robust grid in a changing and uncertain future (also referred to as integrated distribution planning).

**Integrated resource plan (IRP):** A utility plan for meeting forecasted annual peak and energy demand, plus some established reserve margin, through a combination of supply-side and demand-side resources over a specified future period.

**Interoperability:** The capability of two or more networks, systems, devices, applications, or components to externally exchange and readily use information securely and effectively.

**Leadership in Energy and Environmental Design (LEED):** A building rating system, globally recognized for its healthy, highly efficient, and cost-savings. Earning LEED certification represents leadership achievement for sustainability in buildings. Certification is available for new construction and existing buildings for meeting energy, water, construction materials, and other environmental sustainability metrics.

**Load profile:** A building's load profile describes when – time of day or hour of the year – the building is consuming energy (typically used to refer to electricity consumption but can also describe on-site fuel use); load shape and load curve are often used interchangeably, but all refer to the timing of energy use.

**Load shed:** The ability to reduce electricity use for a short time period and typically on short notice. Shedding is typically dispatched during peak demand periods and during emergencies.

**Load shift:** The ability to change the timing of electricity use to minimize demand during peak periods or to take advantage of the cheapest electricity prices. A shift may lead to using more electricity during the cheapest time period and using thermal or battery storage at another time period when electricity prices increase.

**Lost Revenue Adjustment Mechanism (LRAM):** A rate adjustment mechanism that allows a utility to recover revenues that are reduced specifically as a result of EE programs.

**Measure:** An installed piece of equipment or system; or modification of equipment, systems, or operations on end-use customer facilities that reduces the total amount of electrical or gas energy and capacity that would otherwise have been needed to deliver an equivalent or improved level of end-use service.

**Measurement and verification (M&V):** A subset of program impact evaluation that is associated with the documentation of energy savings at individual sites or projects using one or more methods that can involve measurements, engineering calculations, statistical analyses, and/or computer simulation modeling.

**Metrics:** Numbers or other forms of information describing the process of interest, which indicate how the process is performing. Metrics provide a basis for suggesting or making improvements to the process.

**Miscellaneous electrical loads (MELS):** The appliances and devices outside of a building's core functions of heating, ventilation, air conditioning, lighting, water heating, and refrigeration.

**Modulate:** The ability to balance power supply/demand or reactive power draw/supply autonomously (within seconds to sub-seconds) in response to a signal from the Utility during the dispatch period.

**Non-wires solutions:** An electricity grid investment or project that uses nontraditional transmission and distribution (T&D) solutions, such as distributed generation, energy storage, EE, DR, and grid software and controls, to defer or replace the need for specific equipment upgrades, such as T&D lines or transformers, by reducing load at a substation or circuit level.

**Ontology:** a specification of a conceptual model that describes relationships so that data can be exported, translated, queried, and unified across independently developed systems and services.

**OpenADR:** OpenADR is an open, secure, and two-way information exchange model and global Smart Grid standard. OpenADR standardizes the message format used for automated DR and DER management so that dynamic price and reliability signals can be exchanged among utilities, ISOs, and energy management and control systems.

**Peak demand:** The maximum load during a specified period of time.

**Performance-based regulation (PBR):** An approach to regulation designed to strengthen utility performance incentives.

**Schema:** An outline, diagram, or model.

**Semantic interoperability:** The ability of two or more systems to effectively utilize the information that has been exchanged based on a common dictionary of building data, including building automation and control data along with associated systems.

**Smart Home Energy Management System (SHEMS):** A combination of devices and services that manages the energy use of connected devices in a home.

**Smart technologies for energy management:** Advanced controls, sensors, models, and analytics used to manage DERs. GEBs are characterized by their use of these technologies.

**Solar photovoltaics (PV):** Energy radiated by the sun as electromagnetic waves (electromagnetic radiation) that is converted at electric utilities into electricity by means of solar (Photovoltaic) cells.

**Supervisory control:** A functionality that monitors and maximizes synergies between individual end-use systems and optimizes for individual building operation.

**Technical interoperability:** The ability of two or more systems or components to exchange information and to use the information that has been exchanged.

**Thermal energy storage (TES):** A technology that stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used later, either for heating and cooling applications or for power generation.

**Time-varying rates:** Rates that allow the price to vary over some time period to reflect seasonal, diurnal, or hourly changes and designed to modify patterns of electricity usage, including the timing and level of electricity demand. Designs may include time of use (TOU), real-time pricing (RTP), variable peak pricing (VPP), and critical peak pricing (CPP).

**Variable frequency drive (VFD):** An electronic device that varies its output frequency to vary the rotating speed of a motor, given a fixed input frequency. Used with fans or pumps to vary the flow in the system as a function of a maintained pressure.

# Appendix B: GEB Potential Modeling Details

This appendix provides additional detail about the analytical approach, modeling assumptions, and results presented in Chapter 2.

Our approach leveraged several models to characterize hourly EE and demand flexibility measure load shapes and hourly marginal power system costs (see **FIGURE 13**). Specifically, the hourly load shapes of a wide range of EE and demand flexibility measures were developed by LBNL and NREL researchers using EnergyPlus[55] building energy simulations (modeled with the U.S. Department of Energy's (DOE's) ResStock[56] tool for the residential sector and DOE's Commercial Prototype Building Models[57] for the commercial sector). For further detail and discussion of the underlying EE and demand flexibility measure performance assumptions and building simulation assumptions, see the forthcoming paper: "U.S. Building Energy Efficiency and Flexibility as an Electric Grid Resource."[58]

We detail the remaining methodology steps with corresponding sections of Appendix B. Specifically, the steps are: **(1)** Simulating aggregate GEB measure impacts using BTO's Scout model; **(2)** Modifying the impacts to be consistent with estimates of achievable technology adoption; **(3)** Establishing a forecast of power system costs using NREL's Cambium dataset;[59] and **(4)** Using Brattle's LoadFlex modeling framework to evaluate the economic value and $CO_2$ emissions benefits of these achievable estimates of GEB capability. The final section of Appendix B provides additional detailed results that were not included in Chapter 2.

## EE and Demand Flexibility Measure Modeling in Scout

We use Scout, modeling software developed by LBNL and NREL for BTO, to project how regional electricity energy demand will change given the widespread adoption of

55 EnergyPlus™ is DOE's open-source whole-building energy modeling (BEM) engine. More information available at: https://energyplus.net/

56 ResStock™ is a DOE physics-simulation model of the U.S. residential building stock, developed by NREL for the U.S. DOE BTO. More information available at: https://www.nrel.gov/buildings/resstock.html

57 The DOE Commercial Prototype Building Models used are Large Office Detailed, Medium Office Detailed, Warehouse, Large Hotel, and Retail Stand-Alone. More information available at: https://www.energycodes.gov/development/commercial/prototype_models

58 Langevin, Jared; Harris, Chioke B.; Satre-Meloy, Aven; Putra, Handi Chandra; Speake, Andrew; Present, Elaina; Adhikari, Rajendra; Wilson, Eric; and Satchwell, Andrew, "U.S. Building Energy Efficiency and Flexibility as an Electric Grid Resource." Available: https://ssrn.com/abstract=3767157

59 "Cambium is a tool that assembles structured data sets of simulated hourly cost and operational data for modeled futures of the U.S. electric sector with metrics designed to be useful for longterm decision-making." For more background on Cambium see: Gagnon, Frazier, Hale, and Cole, Cambium Documentation: Version 2020, NREL, November 2020, available at: https://www.nrel.gov/docs/fy21osti/78239.pdf

| | | |
|---|---|---|
| 1 | **Define GEB measures** to represent the best commercially available technology for major building end-uses. | **LBNL/NREL analysis** |
| 2 | **Simulate GEB technology performance** for thousands of individual buildings on an 8,760 hourly basis. | **NREL's ResStock & DOE's Commercial Prototype models** |
| 3 | **Scale building characteristics by region**, to align with the size, mix, and weather characteristics of 22 U.S. regions. | **BTO's Scout model** |
| 4 | **Adjust estimates to reflect achievable adoption rates and stock turnover**, based on review of regional and national EE and DR studies. | **Brattle analysis** |
| 5 | **Develop forecasts of system costs and emissions through 2030**, including generation capacity, energy, ancillary services, and transmission capacity. | **NREL's Cambium dataset** |
| 6 | **Evaluate ability of GEB measures to avoid forecasted system costs**, including dynamic dispatch of DF measures. | **Brattle's LoadFlex model** |

**FIGURE 13: METHODOLOGY OVERVIEW**

EE and demand flexibility measures in residential and commercial buildings.[60] EE measures include savings from reducing energy intensity of measure consumption without changing the timing of consumption (e.g., replacing a dishwasher with a more efficient model), whereas demand flexibility measures represent control technologies that actively shift or reduce measure consumption in response to grid-signals (e.g., putting a dishwasher on a timer to run overnight, or reducing lighting during peak price hours).

Each EE measure reflects the adoption of the highest efficiency technology that is commercially available today. The demand flexibility measures model daily, automated load shifting or reduction, rather than relying on consumer behavior (i.e., manual adjustments to end-use loads). Demand flexibility measures do not include EE upgrades; however, we do model "EE+DF" measures which include both an EE upgrade and enablement of demand flexibility (e.g., an electric water heater upgraded to an air-source heat pump based water heater and enabled with smart controls to shift heating demand from peak electricity hours).

The measures used in this analysis were developed by LBNL and NREL, with input from Brattle (see **FIGURE 14**).[61] A few

60 Scout is a modeling tool that assesses the economic and emissions potential of various building technologies in the short- and long-term, accounting for technology stock turnover, EE, cost, and lifetime. Scout scales up building-level hourly energy savings to the regional level using regional building stock data from the EIA's AEO. Industrial buildings are not modeled in Scout and accordingly are not modeled in the GEB *Roadmap*. More information available at: scout.energy.gov.

61 For measure definitions that are generally consistent with those used in this study, see Supplemental Information, Section 4 of Langevin, et al., "U.S. Building Energy Efficiency and Flexibility as an Electric Grid Resource." Available at: https://ssrn.com/abstract=3767157

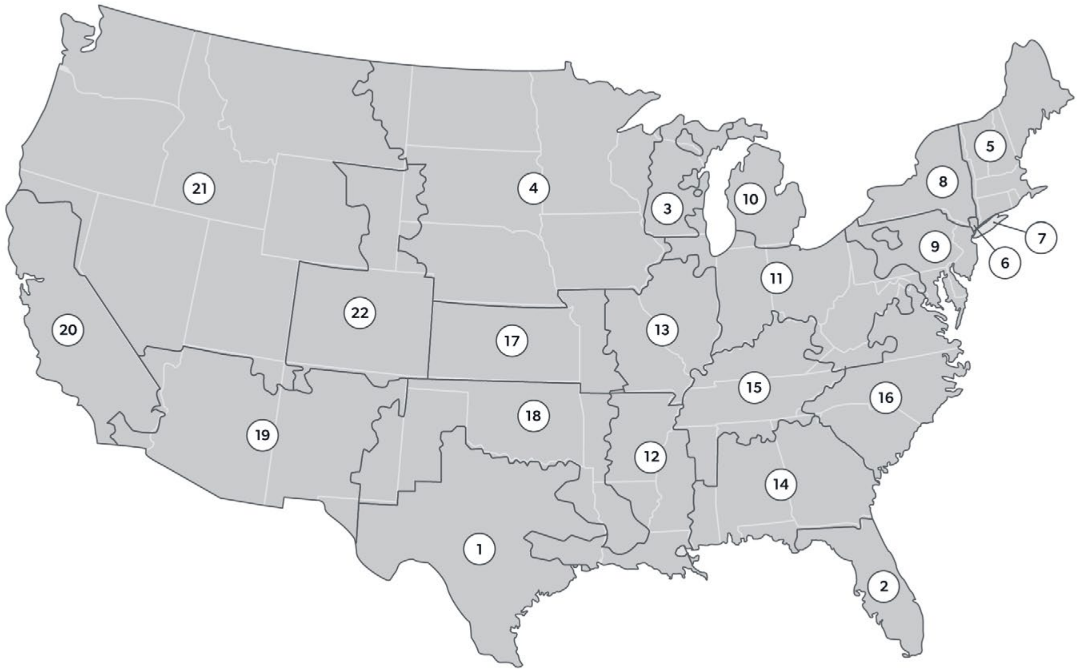
| Energy Efficiency | Energy Efficiency and Demand Flexibility | Demand Flexibility |
|---|---|---|
| Residential Envelope | Residential CAC, ICT, Precond | Residential Preconditioning |
| Residential CAC | Residential ASHP, ICT, Precond | Residential Water Heater |
| Residential ASHP | Res ICT, Envelope, Precond | Residential Clothes Washer |
| Residential CAC, ICT | Residential HPWH | Residential Clothes Dryer |
| Residential ASHP, ICT | Residential Clothes Washer | Residential Dishwasher |
| Residential ICT, Envelope | Residential Clothes Dryer | Residential Pool Pump |
| Residential Lighting | Residential Dishwasher | Residential Electronics |
| Residential Refrigerator | Residential Pool Pump | Commercial HVAC + Pre Cool |
| Residential HPWH | Residential Electronics | Commercial Lighting |
| Residential Clothes Washer | Commercial HVAC, Pre Cool | Commercial MELs |
| Residential Clothes Dryer | Commercial Envelope, Pre Cool | |
| Residential Dishwasher | Commercial Lighting | |
| Residential Pool Pump | Commercial MELs | |
| Residential Electronics | | |
| Commercial HVAC | | |
| Commercial Envelope All | | |
| Commercial Lighting | | |
| Commercial MELs | | |
| Commercial Electric HPWH | | |
| Commercial Refrigeration | | |

| Abbreviations | |
|---|---|
| CAC | Central Air Conditioning |
| ASHP | Air Source Heat Pump |
| ICT | Internet Controlled Thermostat |
| HPWH | Heat Pump Water Heater |
| HVAC | Heating, Ventilation and Air Conditioning |
| MELS | Miscellaneous Electric Loads |
| Precond | Preconditioning |

**TABLE 5: MODELED EE AND DF MEASURES BY CATEGORY**

**Note:** The Commercial Lighting and MELs measures include the secondary HVAC-related effects (i.e., reduced cooling load in the summer due to less thermal losses inside the building).

of the measures differ from those used in previous Scout-based studies in that some of the measures have been disaggregated for the purposes of this analysis (i.e., by separating some bundled measures). With this approach, for example, our analysis allows for a home or commercial building to opt for either an envelope upgrade or an HVAC upgrade individually, rather than necessarily adopting both. All scenarios and corresponding results in the GEB *Roadmap*



| | | | |
|---|---|---|---|
| 1 | ERCT | — | ERCOT All |
| 2 | FRCC | — | FRCC All |
| 3 | MROE | — | MRO East |
| 4 | MROW | — | MRO West |
| 5 | NEWE | — | NPCC New England |
| 6 | NYCW | — | NPCC NYC/Westchester |
| 7 | NYLI | — | NPCC Long Island |
| 8 | NYUP | — | NPCC Upstate NY |
| 9 | RFCE | — | RFC East |
| 10 | RFCM | — | RFC Michigan |
| 11 | RFCW | — | RFC West |
| 12 | SRDA | — | SERC Delta |
| 13 | SRGW | — | SERC Gateway |
| 14 | SRSE | — | SERC Southeastern |
| 15 | SRCE | — | SERC Central |
| 16 | SRVC | — | SERC Vacar |
| 17 | SPNO | — | SPP North |
| 18 | SPSO | — | SPP South |
| 19 | AZNM | — | WECC Southwest |
| 20 | CAMX | — | WECC California |
| 21 | NWPP | — | WECC Northwest Power Pool |
| 22 | RMPA | — | WECC Rockies |

**FIGURE 14: 2019 EMM REGIONS IN THE UNITED STATES**

**Source:** U.S. Energy Information Administration (EIA), "Analysis of the Impacts of the Clean Power Plan," May 2015, Figure 1, p. 6, https://www.eia.gov/analysis/requests/powerplants/cleanplan/pdf/powerplant.pdf

include the full portfolio of measures unless noted otherwise. We assume different measures are adopted at different rates, as discussed later in this Appendix B.

Scout scales up the hourly energy consumption of measures at the building level to the regional level using EIA's Annual Energy Outlook (AEO) regional building stock, energy use, and technology characteristics. We use the 22 EIA Electricity Market Module (EMM) regions (see **FIGURE 14**), and we use the EIA's projections for equipment performance from the 2020 AEO as the EE and demand flexibility measure *baselines*.[62]

Initially, technologies are assumed to be adopted at "max adoption" rates by 2030. "Max adoption," as expressed in the Scout model, assumes new measures are adopted primarily when existing stock (i.e., equipment, appliances, lighting) turns over and when new buildings are built, and to a lesser degree through retrofits.[63] This effectively is an upper-bound on adoption, and assumes that all eligible customers would eventually adopt the technology. The adoption levels are then reduced to reflect expectations about achievable levels of consumer adoption of new technologies, as discussed in the next section.

62 The technology performance projections provided by the AEO include efficiency improvements due to expected improvements in technology as well as efficiency improvements through federal and state efficiency standards.

63 With max adoption, 100% of new stock (from turn-over of existing stock or from new buildings) is assumed to adopt new GEB measures. We use Scout's default retrofit rate of 1%, which represents 1% of existing stock being retrofitted prior to end-of-life. Note that we assume no electrification of onsite combustion loads in the analysis.

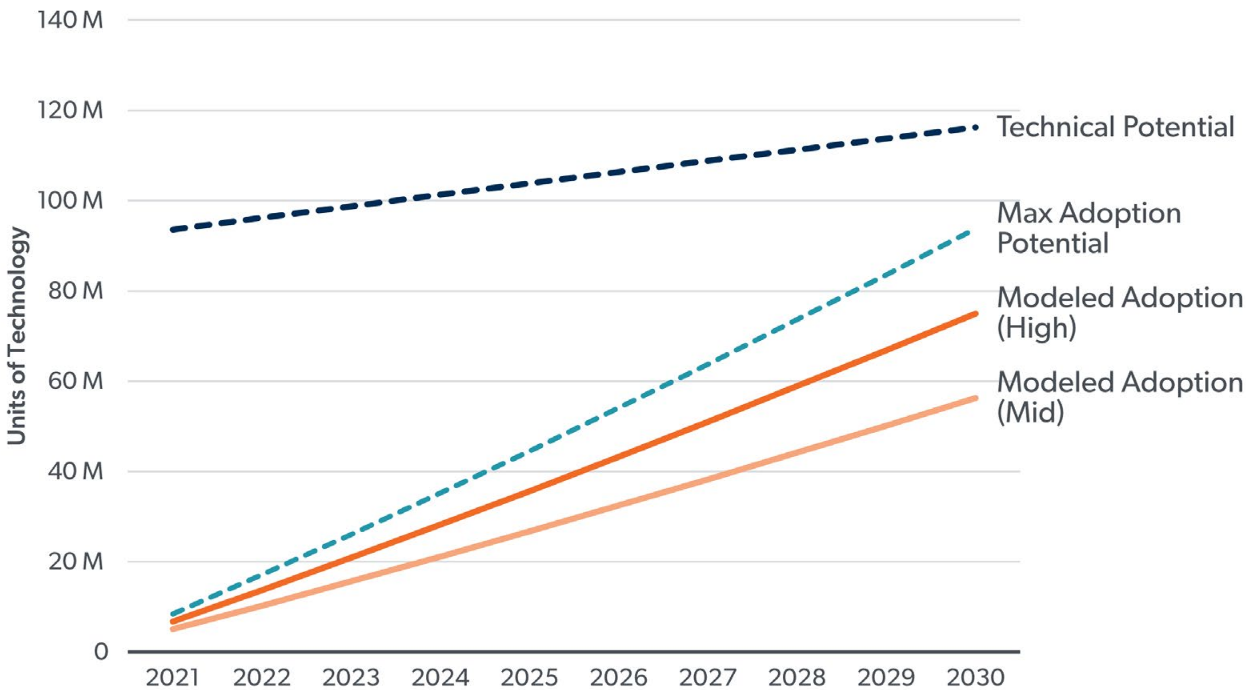



**FIGURE 15:** MODELING OF ACHIEVABLE ADOPTION FOR AN EE RESIDENTIAL DISHWASHER MEASURE

We use Scout to determine each measure's hourly change in energy from the 2030 baseline; we refer to a measure's hourly change in energy from baseline as its "savings profile". We find a measure's savings profile using two Scout outputs: the measure's baseline hourly energy consumption and the measure's "efficient" hourly energy consumption, where the efficient consumption is the consumption after the measure has been implemented. The savings profile is, therefore, the baseline profile subtracted from the efficient profile. These outputs from Scout are an input into Brattle's LoadFlex model.

## Achievable Adoption Rate Assumptions

We model the ***achievable adoption*** of EE and demand flexibility measures by layering realistic rates of consumer technology adoption on top of the "max adoption" potential reflected in the Scout measure outputs, as discussed above. We do this for each measure simply by scaling the measure's baseline and efficient profiles by the assumed participation rate in terms of units of technology adopted each year. Max adoption potential assumes an eventual 100% adoption rate and assumes measures are adopted as eligible stock turns over, new stock is added (e.g., new building), and as existing stock is retrofitted. Our assumed adoption rates "derate" the max potential adoption rate to an achievable level. In contrast, "technical potential" would assume immediate adoption by all eligible stock, rather than waiting for stock to turn over. **FIGURE 15** illustrates the relationship between each of these adoption estimates.

### Demand Flexibility Adoption Assumptions

Assumptions for achievable adoption rates were informed by a review of regional demand flexibility potential studies across the US, the majority of which were from the last five years (see **TABLE 6**). These studies use a variety of methods to establish maximum achievable adoption rates, including primary market research (customer surveys), review of achieved participation in successful demand flexibility programs, interviews with customer account managers, review of utility DR plans, and expert judgment.

| Study | Geographic Coverage | Year | Author |
|---|---|---|---|
| The Potential for Load Flexibility in Xcel Energy's Northern States Power Service Territory | MN, WI, ND, SD | 2019 | The Brattle Group |
| Nova Scotia Energy Efficiency and Demand Response Potential Study for 2021-2045 | Nova Scotia, Canada | 2019 | Navigant Consulting |
| Demand Response Potential in Bonneville Power Administration's Public Utility Service Area | Primarily OR, WA, MT, ID | 2018 | The Cadmus Group |
| "2017 IRP Demand-Side Resource Conservation Potential Assessment Report" | Washington | 2017 | Navigant Consulting |
| State of Michigan Demand Response Potential Study | Michigan | 2017 | Applied Energy Group |
| Demand Response Market Research: Portland General Electric, 2016 to 2035 | Oregon | 2016 | The Brattle Group |
| Estimating Xcel Energy's Public Service Company of Colorado Territory Demand Response Market Potential | Colorado | 2013 | The Brattle Group |

**TABLE 6: POTENTIAL STUDIES USED TO INFORM DF ADOPTION ASSUMPTIONS**

The studies' range in adoption rates for residential demand flexibility measures were grouped by primary end-use (see **FIGURE 16**). Generally, the studies assume adoption rates of 20-30% at the lower end and 50-60% at the higher end, regardless of the end-use. This range in adoption rates is supported by historical data. According to FERC data on utility DR programs, several states have achieved average DLC enrollment rates of 20% or more. On the upper end of the range, some utilities (e.g., Xcel Energy, Otter Tail Power) have enrolled more than half of eligible customers in heating and cooling direct load control programs. Relatedly, data on participation in time-varying rate offerings also supports the assumption that more than 20% adoption is achievable on a voluntary (opt-in basis).[64] For example, APS has enrolled significantly more than half of its residential customers on voluntary TOU rates.

We base our adoption rate assumptions for commercial demand flexibility measures on participation in direct load control, interruptible tariffs, and auto-DR programs with ranges of adoption rates grouped by primary end use (see **FIGURE 17**). There is a wider range of adoption rates for commercial customers than residential among end-use groupings. Generally, adoption rates can range from less than 10% to about 40%. We note a few observations behind the data: 1) Larger customers tend to have higher adoption potential than smaller customers; 2) Interruptible tariffs have the highest adoption potential and typically do not require advanced technology deployment (though may involve partnering with an aggregator); and 3) Estimates of ADR adoption potential are varied and the data is fairly limited.

64 U.S. DOE, Smart Grid Investment Grant Program, "Final Report on Customer Acceptance, Retention, and Response to Time-Based Rates from the Consumer Behavior Studies," November 2016, https://www.smartgrid.gov/document/CBS_Results_Time_Based_Rate_Studies.html

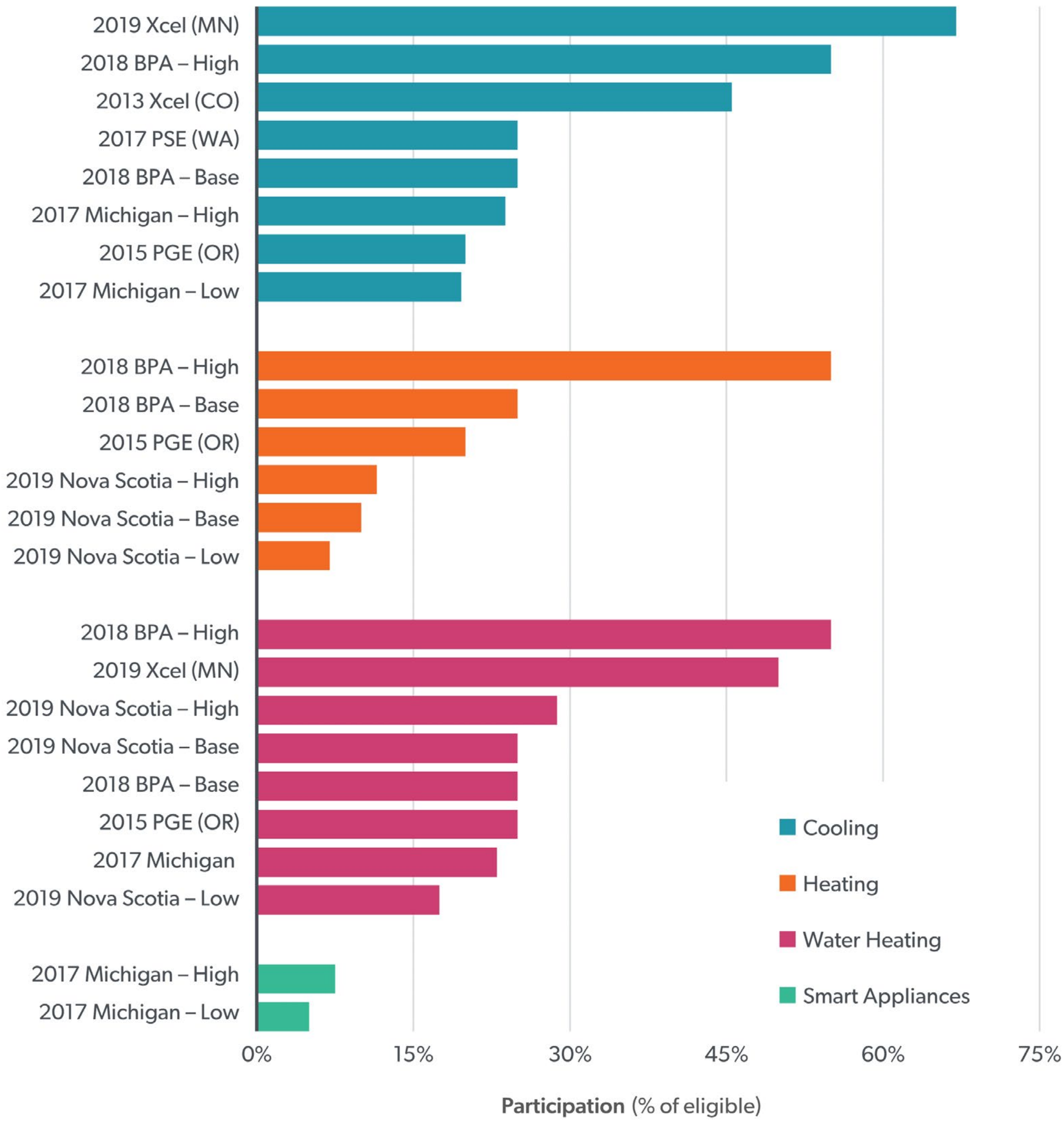



**FIGURE 16: RESIDENTIAL LOAD CONTROL ADOPTION POTENTIAL FROM SURVEYED STUDIES**

The following principles guided our approach to using the previously discussed data to establish adoption rate assumptions for the GEB *Roadmap*. First, we tie the assumptions directly back to the ranges observed in the demand flexibility potential studies discussed above. Second, we only use as much precision as is supported by the data. And third, we use more conservative adoption rates for measures that have had less commercial exposure. **TABLE 7** shows the assumed participation rates for demand flexibility measures across the three main cases (e.g., Low, Mid, and High).

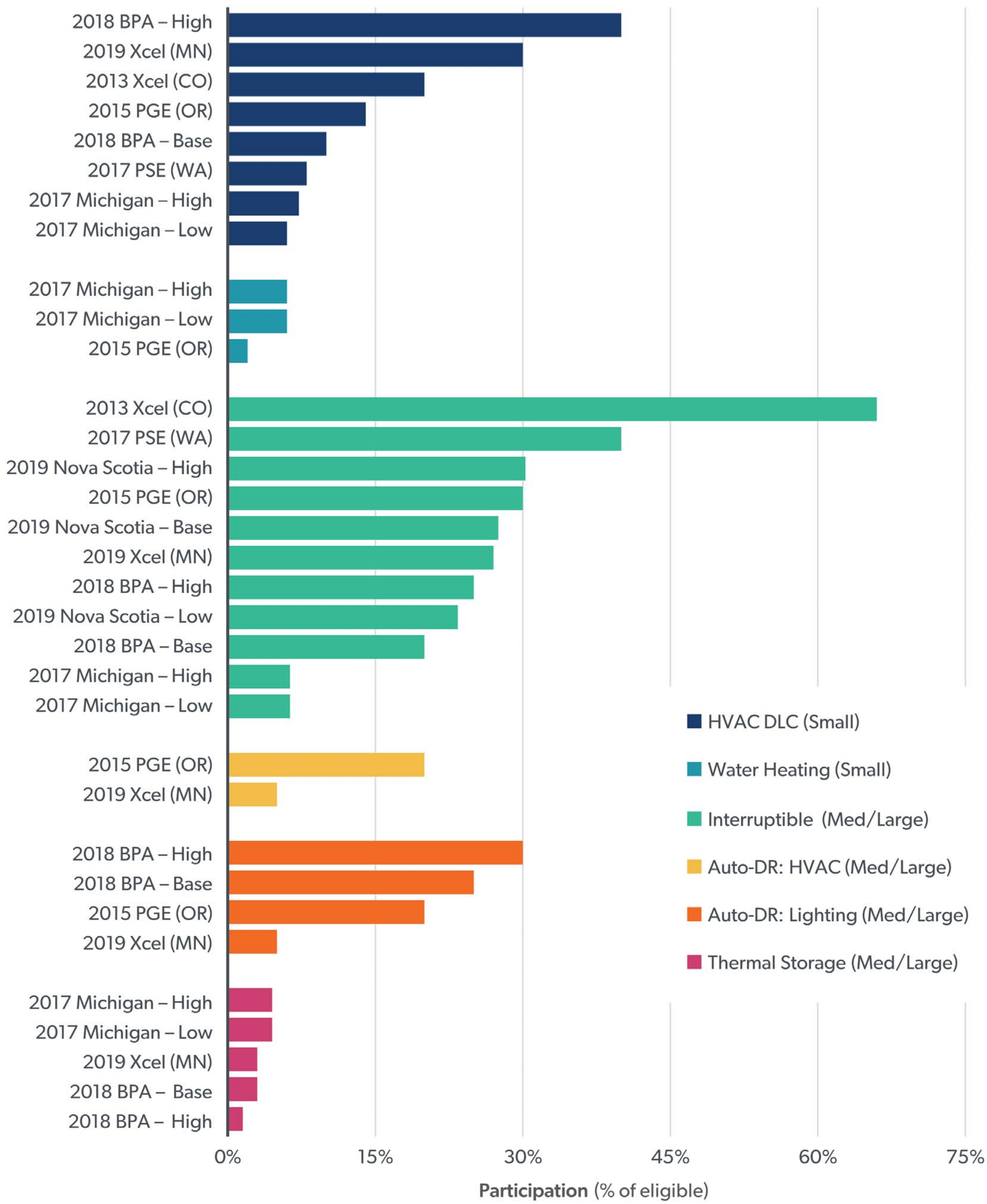



**FIGURE 17: COMMERCIAL DF ADOPTION POTENTIAL FROM SURVEYED STUDIES**

| | Low | Mid | High |
|---|---|---|---|
| **RESIDENTIAL** | | | |
| **Thermostat**[1] | 20% | 30% | 55% |
| **Water heating** | 20% | 30% | 55% |
| **Pool Pump** | 20% | 30% | 55% |
| **Smart appliances**[2] | 5% | 15% | 25% |
| **COMMERCIAL** | | | |
| **HVAC** | 10% | 25% | 40% |
| **Lighting** | 10% | 25% | 40% |
| **Misc. Electric Loads** | 5% | 15% | 20% |

**TABLE 7: DEMAND FLEXIBILITY CUMULATIVE ADOPTION RATES ASSUMED IN GEB ROADMAP BY END-USE (2021–2030)**

**Note:** Adoption rates are expressed as a percentage of eligible participants.

## EE Adoption Assumptions

Similar to the approach with demand flexibility adoption, we base our EE adoption assumptions on an extensive review of recent regional EE potential studies across the U.S. (see **TABLE 8**). The reviewed EE potential studies use the same methods used in the demand flexibility potential studies to establish achievable adoption rates. Most studies conduct surveys on customer's willingness to adopt at varying incentive payment levels (i.e., incentives that would cover portions of the incremental cost of the measure).

The projected residential and commercial adoption rates for EE vary widely due largely to different responses to a range of incentive levels, differences in regions being studied, and different forecasting methodologies across studies. **FIGURE 18** shows the distributions of residential end-use adoption rates, and **FIGURE 19** shows the distribution of commercial end-use adoption rates. Note there is generally a large amount of data available for each end-use (i.e., > 10 data points), though some emerging EE measures, such as residential smart thermostats and residential pool pumps have less data available.

We establish low, mid, and high adoption assumptions for the GEB *Roadmap* using the adoption rate distributions from the surveyed studies (see **FIGURE 24**). We ground the mid-case assumptions in the mean of the distribution, rounding to the nearest 5%. The high and low cases are based on the mean +/- one standard deviation, again rounding to the nearest 5%. There are a few exceptions to this general method. In the case of the envelope measures, residential electronics, and commercial plug-loads, the adoption rates reported by the studies correspond to a subset of a building's envelope (e.g., roof insulation) and a subset of electronics or plug-loads (e.g., computers), whereas the Scout measures encapsulate the whole envelope and all electronics and plug-loads. For this reason, these participation rates may overstate the adoption of the all-encompassing measures modeled by Scout. To account for this, we manually reduced the assumed participation rates for those measures by 20 percentage points.

| Study | Geographic Coverage | Year | Author |
|---|---|---|---|
| Consumers Energy Electric Energy Efficiency Potential Study | Michigan | 2016 | GDS Associates |
| 2015 Demand Side Management Potential Study (for Colorado Springs Utilities) | Colorado | 2016 | The Cadmus Group |
| A Guide to Growing an Energy-Efficient Economy in Mississippi | Mississippi | 2013 | American Council for an Energy-Efficient Economy |
| Energy Efficiency Potential Study for Pennsylvania | Pennsylvania | 2015 | Statewide Evaluation Team et al. |
| Vermont Department of Public Service Energy Efficiency Potential in Vermont | Vermont | 2018 | GDS Associates and The Cadmus Group |
| Energy Efficiency Potential Study (for Louisville Gas and Electric and Kentucky Utilities) | Kentucky | 2013 | The Cadmus Group |
| The $20 Billion Bonanza: Best Practice Electric Utility Energy Efficiency Programs and Their Benefits for the Southwest | AZ, CO, NV, NM, UT, WY | 2012 | Southwest Energy Efficiency Project |
| Electric Demand Side Management (DSM) Market Potential Study (for Otter Tail Power Service Co.) | Minnesota | 2016 | Navigant Consulting |
| Seventh Northwest Conservation and Electric Power Plan | ID, MT, OR, WA | 2016 | Northwest Power and Conservation Council |
| DTE Energy Electric Energy Efficiency Potential Study | Michigan | 2016 | GDS Associates |
| 2016-2018 Energy Efficiency Plan | Massachusetts | 2015 | MA Energy Efficiency Advisory Council |
| Indianapolis Power & Light Company 2014 Integrated Resource Plan | Indiana | 2014 | Applied Energy Group |
| Ameren Illinois Demand Side Management Market Potential Study | Illinois | 2016 | Applied Energy Group |
| Focus on Energy 2016 Energy Efficiency Potential Study | Winsconsin | 2017 | The Cadmus Group |

**TABLE 8:** REVIEWED EE POTENTIAL STUDIES

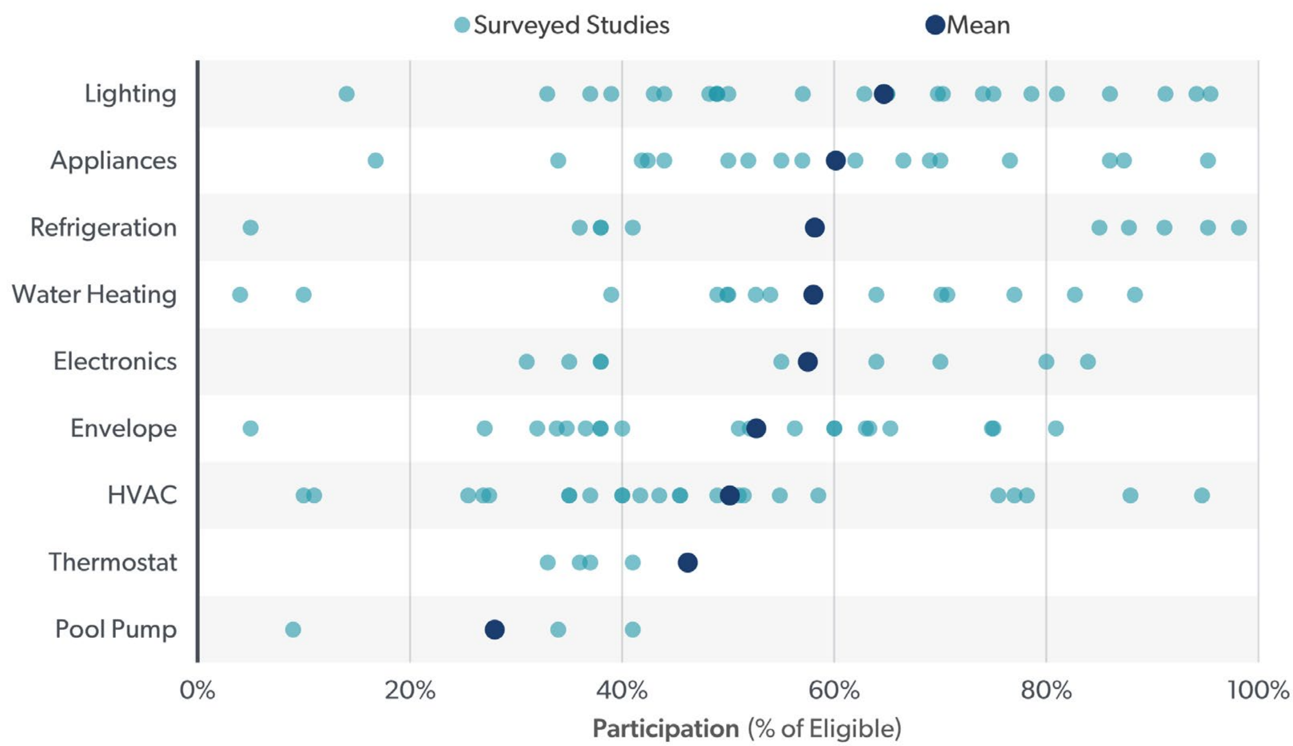



**FIGURE 18:** RESIDENTIAL EE – ADOPTION RATES FROM LITERATURE REVIEW

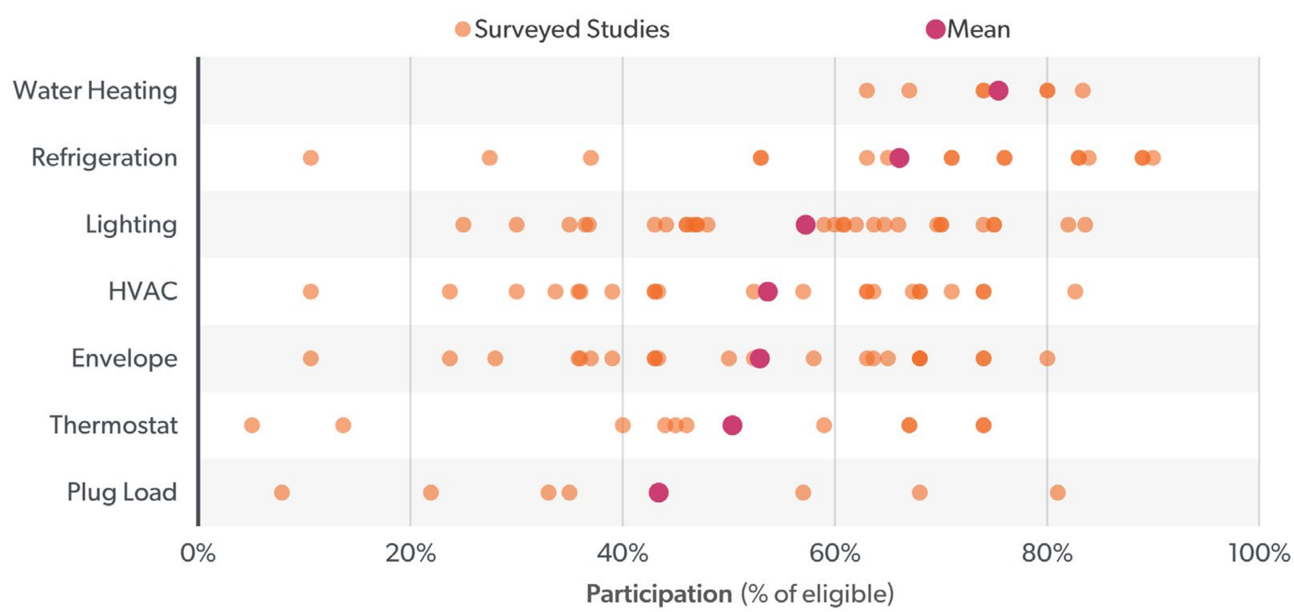



**FIGURE 19:** COMMERCIAL EE – ADOPTION RATES FROM LITERATURE REVIEW

## Accounting for Overlapping Market Segments

Measures can overlap or "compete" in their market segment. For example, the same consumers who are eligible for a residential EE+DF water heating measure also could choose to adopt only the EE or DF water heating measure. Therefore, it is important to ensure that the aggregate adoption rates of EE, DF, and EE+DF measures for the same end-use are consistent with the assumed end-use

| | Low | Mid | High |
|---|---|---|---|
| **RESIDENTIAL** | | | |
| Lighting | 45% | 65% | 85% |
| Appliances | 40% | 60% | 80% |
| Refrigeration | 30% | 60% | 90% |
| Water Heating | 40% | 60% | 80% |
| Electronics | 20% | 40% | 60% |
| Envelope | 10% | 30% | 50% |
| HVAC | 30% | 50% | 70% |
| Thermostat | 30% | 45% | 60% |
| Pool Pump | 20% | 30% | 40% |
| **COMMERCIAL** | | | |
| Water Heating | 65% | 75% | 85% |
| Refrigeration | 45% | 65% | 85% |
| Lighting | 35% | 55% | 75% |
| HVAC | 35% | 55% | 75% |
| Envelope | 10% | 30% | 50% |
| Thermostat | 30% | 50% | 70% |
| Plug Load | 10% | 20% | 30% |

**TABLE 9: ENERGY EFFICIENCY CUMULATIVE ADOPTION RATES ASSUMED IN GEB ROADMAP, BY END-USE (2021–2030)**

**Note:** Adoption rates are expressed as a percentage of eligible participants.

adoption rate established in **TABLE 7** and **TABLE 9**. We remain consistent with these end-use adoption rates by allocating participation between overlapping measures. We assume that the adoption of an EE+DF measure counts towards both the corresponding EE end-use adoption rate and the corresponding DF end-use adoption rate. We also assume that 80% of DF participants will also participate in EE, reflecting the notion that a consumer that is likely to adopt a DF measure is also like to adopt the corresponding EE measure (e.g., the incremental cost of enabling the DF controls is lower when simultaneous installing an EE measure). **FIGURE 20** shows an illustrative example of how we allocate adoption rates for the residential HPWH EE, DF, and EE+DF measures (i.e., residential water heating measures) based on the following equations:

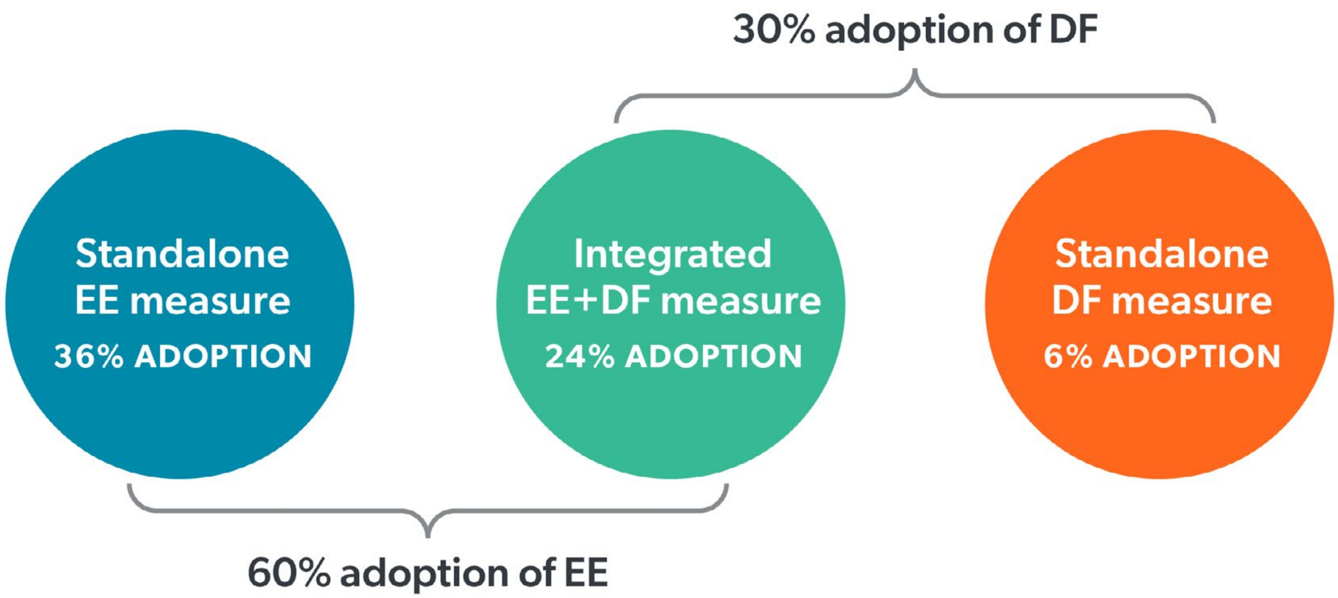



**FIGURE 20:** ILLUSTRATIVE EXAMPLE FOR RESIDENTIAL WATER HEATING

$$X_{EE}+Y_{EE+DF}=0.6, \qquad Y_{EE+DF}+Z_{DF}=0.3, \qquad \frac{Y_{EE+DF}}{Y_{EE+DF}+Z_{DF}=0.8,}=0.8$$

where variables $X_{EE}$, $Y_{EE+DF}$, and $Z_{DF}$ represent specific adoption rates for the residential HPWH (EE), residential HPWH (EE+DF), and residential HPWH (DF) measures, respectively, and the end-use adoption rates are 60% for EE and 30% for DF. We then solve the equations for the three unknown adoption rates.

## Marginal System Costs

We model multiple power system benefits of deploying EE and demand flexibility measures, including avoided generation capacity costs, avoided marginal energy costs, avoided ancillary service costs, avoided transmission capacity costs, and avoided $CO_2$ emissions. All but the transmission capacity costs and ancillary service costs are based on NREL's Cambium dataset, which provides hourly marginal system costs for select Standard Scenarios.[65] We use the following scenarios from the 2020 Standard Scenarios dataset: Mid Case, High Renewable Energy Cost, and Low Renewable Cost. These scenarios are used in the GEB Roadmap cases as follows: The Standard Scenarios Mid Case is used for the *Roadmap's* main cases (e.g., Low Adoption, Mid Adoption, High Adoption), as well as the High Capacity Value case. The Standard Scenarios High Renewable Energy Cost is used for the *Roadmap's* Low Renewable case, where "Low Renewable" refers to the level of renewable deployment. Conversely, the Standard Scenarios Low Renewable Cost is used for the *Roadmap's* High Renewables case.

### Representative Balancing Areas

Cambium provides system cost data for each of 134 balancing areas (BAs) across the lower 48 states of the U.S., while the Scout outputs are for the larger, 22 EMM regions. We make the two datasets geographically compatible by selecting a single representative BA for each EMM region; the BA's system costs are then used to represent those of the entire EMM region.

We select the BA in each EMM region with an hourly energy cost shape that is most representative of all BAs in the region. We use four key statistics to characterize the shape of the cost

65 See Standard Scenarios, National Renewable Energy Laboratory (NREL): https://www.nrel.gov/analysis/standard-scenarios.html and NREL's Scenario Viewer and Data Downloader available at: https://cambium.nrel.gov/

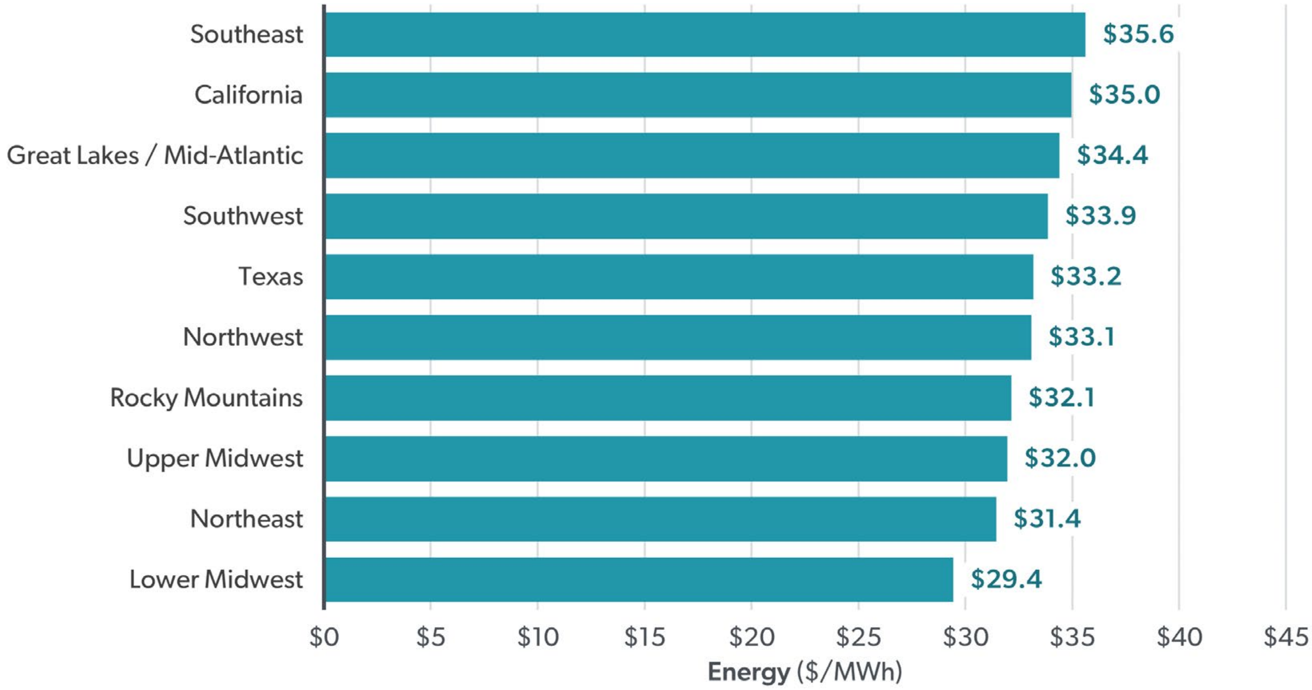



**FIGURE 21: AVERAGE MARGINAL ENERGY COSTS BY AVERT REGION IN 2030**

time-series: seasonal mean, seasonal standard deviation, mean of the daily range (by season), and max of the daily range (by season). We also find the weighted average of each statistic across all BAs in the EMM region, where the weighting is each BA's seasonal load. The representative BA is selected as the BA whose statistics minimize the sum-of-squared errors from the BAs' weighted average statistics.

We select the representative BAs based on the Mid Case Standard Scenario's marginal energy costs, and use the same representative BAs for the High Renewable Cost and Low Renewable Cost Standard Scenarios. In addition to representing the EMM's marginal energy costs, the representative BA also is used to establish the EMM's marginal capacity costs, ancillary service costs, and $CO_2$ emissions.

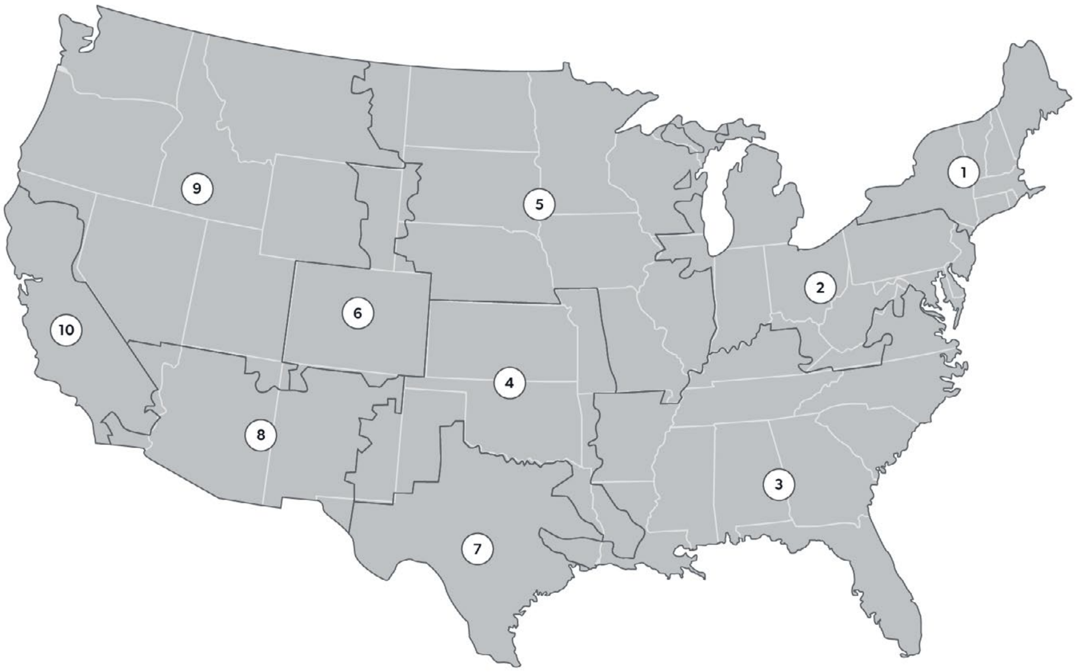
We apply a scaling factor to the representative BA's system costs to account for the possibility that a representative BA might be selected with a relatively low share of the EMM's load and might under- or over-represent the EMM's system costs. One scaling factor is used per data type (marginal energy costs, capacity costs, and $CO_2$ emissions) and per EMM region. For example, the scaling factor for marginal energy costs ensures that, when the factor is applied to the representative BA's marginal energy costs, the resulting total cost of energy to serve the EMM's load is the same as when the BAs' energy costs are calculated separately and then summed.

## Energy Costs

**FIGURE 21** shows the resulting marginal energy costs by AVERT region projected for 2030, with original cost data sourced from the Mid Case Standard Scenario. In 2030, average energy costs range from about $30-$35/MWh. We report all results at the AVERT region level (see **FIGURE 22**) and all costs are reported in 2019 dollars.

## Generation Capacity Costs

We use Cambium's capacity cost data and use the representative-BA approach described above to develop an hourly marginal capacity cost time-series for each EMM




1 **NE** — Northeast
2 **EMW** — Great Lakes / Mid-Atlantic
3 **SE** — Southeast
4 **SC** — Lower Midwest
5 **WMW** — Upper Midwest
6 **RM** — Rocky Mountains
7 **TX** — Texas
8 **AZNM** — Southwest
9 **NW** — Northwest
10 **CA** — California

**FIGURE 22: AVERT REGIONS IN THE UNITED STATES**

**Source:** U.S. Environmental Protection Agency (EPA), "AVoided Emissions and geneRation Tool (AVERT) User Manual Version 1.3," October 2015, https://19january2017snapshot.epa.gov/sites/production/files/2016-04/documents/avert_user_manual_11-06-15_508.pdf

region.[66] The exception is in the High Capacity Value Case, where we take the representative hourly marginal capacity costs from the Mid Adoption Case and scale the costs up by a constant factor in each hour so that the sum of the hourly costs across the year is $75/kW-yr.[67] The average generation capacity costs for the Mid Adoption Case range from $15-$60/kW-yr depending on the region (see **FIGURE 23**).

Cambium allocates capacity costs to the highest net load hours.[68] Because the Scout and Cambium results are based on different underlying weather assumptions, it was necessary to align peak load conditions from Cambium with those of the aggregate building profiles in Scout. To do this, we shifted the hours to which Cambium allocates capacity costs to reflect the rank order of system-wide regional building demand on a seasonal basis. While the resulting total cost of capacity is the same across the year, this adjustment better reflects the value of building loads to reduce system peak demand on an hourly basis.

66 Capacity costs in Cambium are defined as the "estimate of the cost of additional capital investment incurred by a unit of marginal end use load." Cited from: Pieter Gagnon to The Brattle Group, July 13, 2020, NREL, Memo detailing Descriptions of the variables included in the January 2020 release of Cambium data.

67 $75/kW-yr represents a higher, but still reasonable, generation capacity cost based on our review of capacity auction results and resource adequacy contracts.

68 Cambium documentation describes the method of allocation as follows, "The marginal cost of an additional MW of firm capacity is allocated to each BA's highest net load hours as a heuristic for the hours with the highest loss-of-load probability. Therefore, the sum of a year's capacity costs across a BA is the cost of an additional MW of firm capacity." Cited from: Ibid.

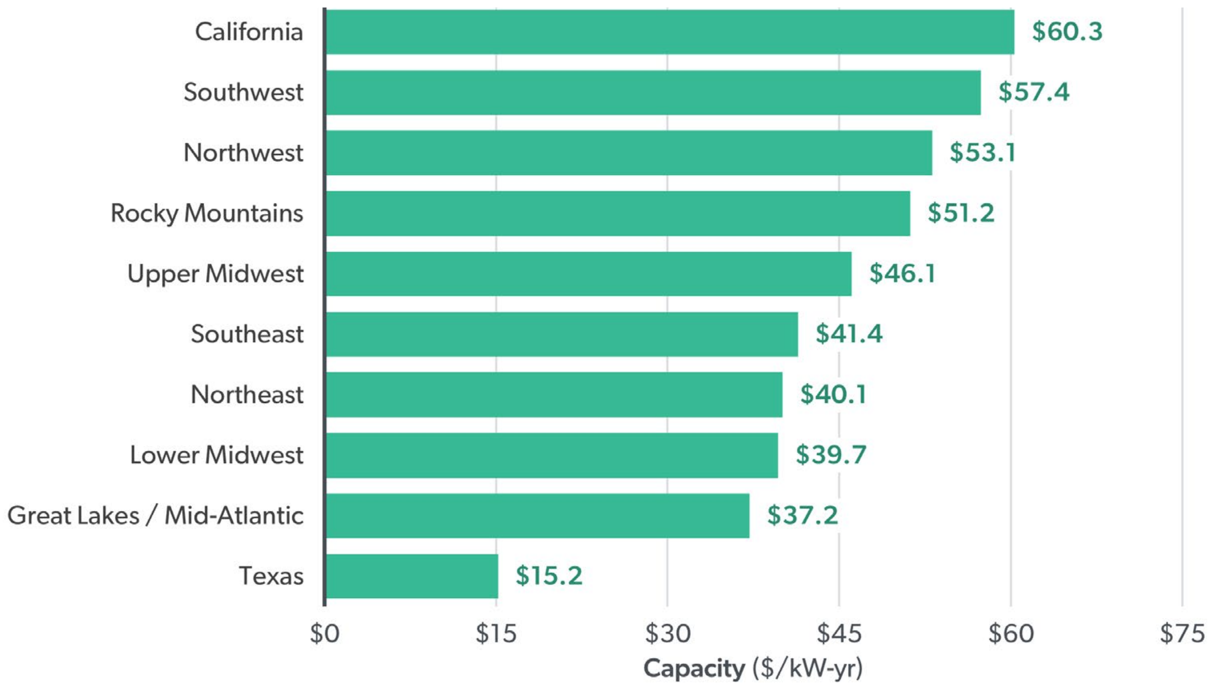



**FIGURE 23: AVERAGE GENERATION CAPACITY COSTS BY AVERT REGION IN 2030**

## Ancillary Service Costs

We primarily base ancillary service costs on historical ancillary service price data from ISOs and RTOs to fully reflect market factors that influence these prices but cannot be readily captured through optimization modeling frameworks like those used to create the Cambium data. Regulation and spinning reserve prices from 2019 are compiled from CAISO, MISO, SPP, NYISO, ISO-NE, and PJM. These prices are then mapped to the EMM regions and converted from $/MW of service to $/MWh of end-use load. We then map the highest historical prices to the hours in Cambium with the highest ancillary service costs (and the lowest prices to Cambium's lowest cost hours), so that the timing of high ancillary service costs is temporally consistent with the other Cambium data. We do this by ranking Cambium's hours by ancillary service cost and mapping the ranked historical data to them.

## Transmission Capacity Costs

Transmission costs are allocated using the same shape as generation capacity costs, scaled by a constant factor in each hour to reflect the total avoided cost ($15/kW-yr). In the High Capacity Value case, a higher total avoided cost is assumed ($30/kW-yr). While avoided transmission capacity costs are system-specific assumptions that can vary widely from one utility system to the next, our estimates are within the range of assumptions from a variety of studies on the value of EE.[69]

## $CO_2$ Emissions Rates

We use hourly long-run marginal emissions rates from NREL's Cambium dataset as the basis for our hourly $CO_2$ emissions profiles. As with energy and capacity prices, we transform the BA-level data into a single representative hourly profile for each EMM region, using the representative-BA method described above.

69 For example, a study by The Mendota Group summarizes the range of transmission capacity benefits observed in various EE studies. See Mendota Group, "Benchmarking Transmission and Distribution Costs Avoided by Energy Efficiency Investments," for Public Service Company of Colorado, October 23, 2014. Also, EPRI's 2014 report "U.S. Energy Efficiency Potential Through 2035" assumed avoided transmission costs of $15/kW-yr.

Note that emissions reductions represented in our study are for $CO_2$ only, not $CO_2e$ (i.e., $CO_2$ equivalent) emissions, due to data availability.

## Economic Analysis

The Brattle Group's LoadFlex model[70] was adapted to calculate the potential value of EE and demand flexibility in 2030, using the EE and demand flexibility measure profiles derived from BTO's Scout model, as well as energy, capacity, and ancillary service costs from NREL's Cambium dataset and historical ISO and RTO prices, as described above.

At a high level, LoadFlex is used to calculate EE measure value at the EMM region level by multiplying static hourly savings profiles by hourly system costs. Demand flexibility measure value is calculated by dynamically dispatching measures against hourly system costs. **FIGURE 24** shows an example dispatch of the residential HVAC EE+DF measure and how it reduces system costs. The EE component of the measure results in reductions to measure load during all hours with significant baseline usage. The demand flexibility component is dispatched to reduce load during the system's highest-cost hours (19–22), requiring load-building during hours 15–18.[71] Periods of load building are defined as periods when a dispatched measure's load is higher than its baseline (in this example, the applicable baseline is the "With EE" dashed line). Load building occurs for almost all demand flexibility measures because we assume a measure's end-use (e.g., dishwashing) is still delivered to the consumer, but at a different time of day, or that a measure's end-use (e.g., space cooling) must remain within occupant comfort ranges.[72] Details on the constraints applied to demand flexibility measure dispatch and how we used the cost data derived from Cambium to estimate total power system value follow below.

### Energy Efficiency

To calculate the economic benefits of EE, hourly measure savings profiles from Scout were adjusted to reflect achievable levels of technology adoption, and then multiplied by hourly costs of energy, capacity, ancillary services, and transmission. We derated the savings on energy and capacity to account for declining incremental value of savings (see discussion of declining incremental value in this appendix below).

### Demand Flexibility

We used Brattle's LoadFlex model to calculate the economic benefits of DF. The LoadFlex model optimizes each day's dispatch of demand flexibility measures to maximize economic savings.

LoadFlex is used to simulate the hours of dispatch for each measure, which maximizes the economic benefits across energy, generation capacity, ancillary services, and transmission capacity. If on any day, the cost of shifting a measure's load from its baseline exceeds the benefits of doing so, the measure is not dispatched (i.e., no load is shifted from baseline).[73] The dispatch of each measure is constrained by the physical behavior of each measure as represented in Scout. The constraints can be categorized as constraints on a measure's **load reduction** and **load building** behavior and are defined as follows:

70 For further discussion, see Hledik, Ryan, Ahmad Faruqui, Tony Lee, and John Higham, "The National Potential for Load Flexibility: Value and Market Potential Through 2030," June 2019.

71 Note that this optimization is performed to minimize *system costs*, not to minimize measure peak demand.

72 For example, during the cooling season, the residential preconditioning measure is defined such that thermostat setpoints are decreased by 3 degrees F to pre-cool the space for four hours prior to the load reduction period. During the load reduction period, thermostat set points are increased by 3 degrees F relative to the original setpoint. Pre-cooling results in load building, but also enables more load reduction during the load reduction period while maintaining occupant comfort.

73 This is particularly possible for measures in which dispatching for demand flexibility results in an average overall increase in load over the course of the day.

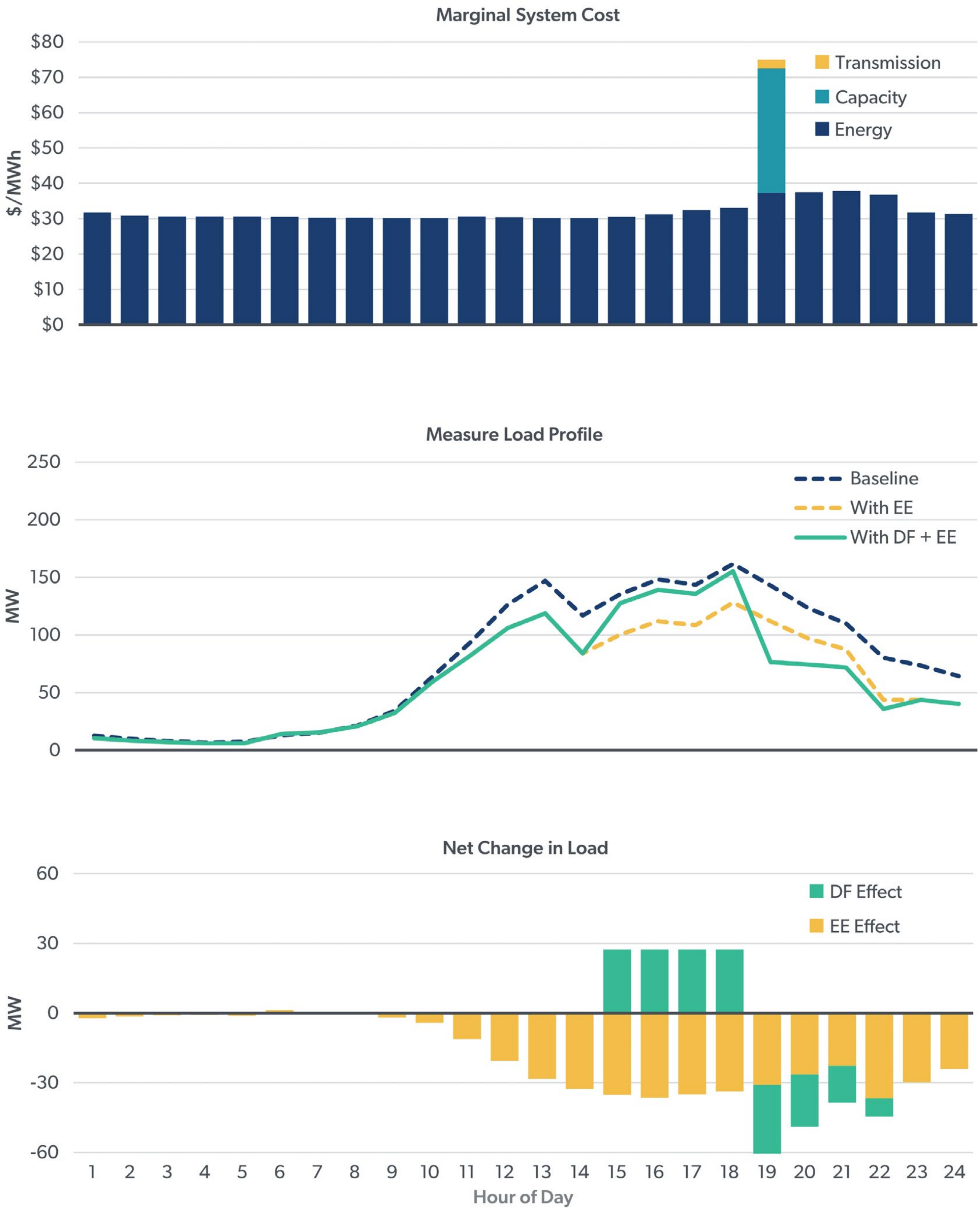



**FIGURE 24: EXAMPLE DISPATCH FOR RESIDENTIAL HVAC MEASURE (CAC, ICT, AND PRECONDITIONING) AUGUST 13, 2030 IN NEW ENGLAND**

## Load Reduction Constraints

- A measure's load reduction can only happen once each day, across four consecutive hours.
- The shape of the measure's load reduction during these four hours is taken from the savings profile from Scout, at the granularity of Measure x EMM Region x Day.
- For example, if the measure's Scout savings profile shows savings of 25% of baseline in hour 1, 20% in hour 2, 15% in hour 3, and 10% in hour 4, then load reductions are allowed in any consecutive four hours of the day, with reductions calculated based on the same shape (e.g., 25% in hour 1, 20% in hour 2).

## Load Building Constraints

- A measure's load building is constrained by the ratio of load building to load reduction (MWh to MWh) observed in its Scout savings profile. This ratio is calculated at the granularity of Measure x EMM Region x Week.
  - For instance, consider **FIGURE 30**. The load building to load reduction ratio shown in Scout for the New England Residential CAC, ICT, and Preconditioning measure for the week of August 13, 2030 was 1.00:1.03. Therefore, the 162 MWh of DF-enabled energy savings occurring in hours 19–23 must be accompanied by 158 MWh of load-building (green bars in hours 15–18).
  - This ratio is calculated on a weekly basis to smooth out irregularities observed at shorter time intervals in the Scout output.
- Load building is assumed to be spread evenly over each hour, in equal MWh increments.
- A measure's load building is also constrained in its relative timing to when load reduction occurs. There are six options for this constraint, which varies by the type of measure, as informed by Scout documentation and model outputs:
  - **Option 1:** Load building occurs in the four hours prior to load reduction. Applies to, for example, HVAC preconditioning measures.
  - **Option 2:** Load building can occur in the four hours prior to ***or*** following load reduction. Applies to, for example, residential clothes dryer measures.
  - **Option 3:** Load building occurs in the two hours following load reduction. Applies to residential electronics measures.
  - **Option 4:** Load building occurs over any four hours of the day. Applies to residential pool pump measures.
  - **Option 5:** Load building occurs over any two hours of the day. Applies to residential water heating measures.
  - **Option 6:** No load building occurs. Applies to commercial lighting and MELs measures.

In addition to the energy, capacity, transmission, and ancillary service benefits provided by each demand flexibility measure, we assume that water heaters are able to add system value by providing frequency regulation. We assume that water heaters can provide up to 50% of a region's regulation requirement, as defined in the Cambium dataset, and we assume they can sell a quantity of up to 50% of their average baseline demand. To ensure deliverability, we restrict water heaters to only sell regulation during hours in which they are not dispatched for energy.

## Declining Incremental Value

While the first megawatt of demand reduced is valued at the marginal cost of meeting demand (i.e., the market clearing price in a competitive market), subsequent megawatts of demand reduction provide less energy and generation capacity value.[74] We refer to this as the declining incremental value of demand reduction.

To estimate the rate at which energy value should decline, we constructed energy supply curves based on the capacities and short-run marginal costs of the generators in the Cambium dataset.[75] We converted these installed capacity (ICAP) values into unforced capacity (UCAP) values using established capacity credit estimates.[76] We then fitted a linear regression to the curve to estimate the price effect of adding or subtracting one MW of demand.

To estimate the declining value of avoided capacity costs, for all regions we use NYISO's "ICAP/UCAP Translation of Demand Curve"[77] to approximate a 5% decrease in capacity price for each 1% decrease in UCAP. We use the Cambium data to determine the MW value associated with 1% of each region's UCAP, and then adjust prices based on savings from EE and DF. Note that demand flexibility is dispatched economically against prices after considering the EE effect, but before considering the demand flexibility effect. In essence, we therefore assume that each demand flexibility unit dispatches without knowledge of the behavior of other demand flexibility units on the system.

### Avoided $CO_2$ Emissions

After optimizing dispatch to maximize the power system value of each demand flexibility resource, we multiply the hourly EE and demand flexibility savings profiles from our economic model against Cambium's hourly long-run marginal emissions rates by EMM-region to estimate the long-run emissions reductions from each measure.

## Detailed Findings

This section presents five key findings as well as summary tables of energy savings and peak demand savings. Results presented correspond to the Mid Adoption Case, except for Key Finding 5, which corresponds to the Low RE and High RE Cases.

### Putting the Energy Savings Into Context

**FIGURE 25** shows the GEB energy savings estimates relative to total U.S. electricity sales. First, the analysis considers only residential and commercial building loads (1). Of that load, certain efficiency and demand flexibility improvements were not analyzed for certain end-uses (2). A portion of that remaining load would not be eligible for EE and demand flexibility technologies in our analysis since the applicable end-uses would not yet have reached the point of requiring replacement (3). Of the remaining load, only a portion of consumers are assumed to voluntarily adopt the EE and/or demand flexibility measures. This results in 792 TWh of end-use load that is "participating" in EE and demand flexibility measures in 2030. GEB savings represent **36%** of that participating end-use load, or 7% of total electricity sales (see **FIGURE 25**).

### Seasonal Average Load Impact Profiles

Space heating and cooling (HVAC) measures contribute most to savings and drive the seasonal difference between the aggregate savings profiles. **FIGURE 26** and **FIGURE 27** show the average

74 This dynamic also exists for transmission and ancillary services value. Due to data limitations and already conservative estimates of those value streams, we assume that they retain their marginal value for all EE and DF reductions. Note that while this discussion focuses on the declining incremental value associated with demand reduction, we assume effects to be symmetrical – incremental value increases with demand growth.

75 We grouped the small New York EMM regions together to approximate the effect of NYISO, the New York-wide market.

76 For applicable resources, we approximated capacity credits using ISO-NE's Net CONE model, available at: https://www.iso-ne.com/committees/markets/markets-committee/. For resources unavailable here (nuclear, geothermal, and hydro), we derived estimates using monthly capacity factor data from EIA, available at: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b.

77 Available at: https://www.nyiso.com/documents/20142/5624348/ICAP-Translation-of-Demand-Curve-Summer-2019.pdf/e1988852-3fcf-281c-4ac7-dff12d078507.

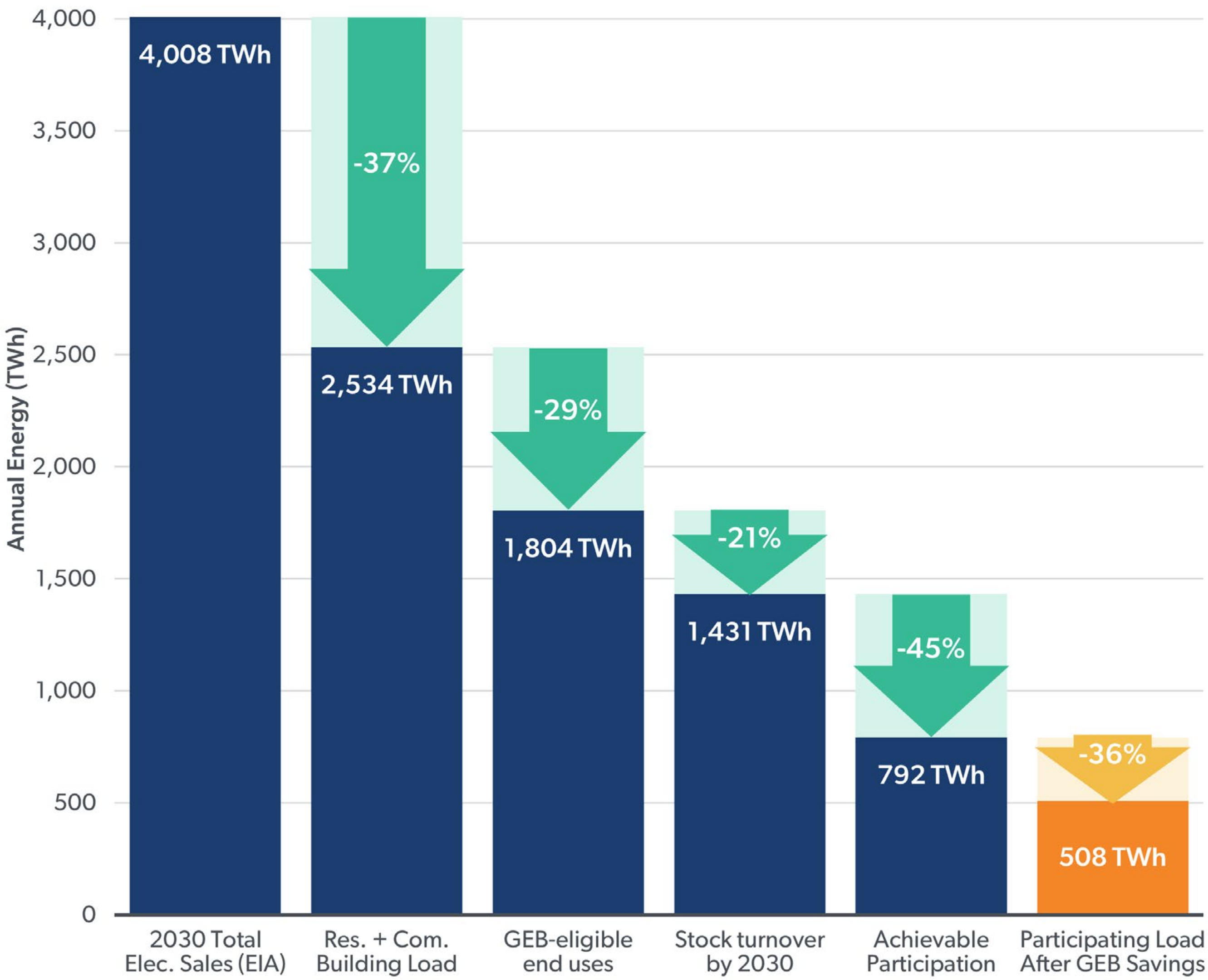



**FIGURE 25: CHARACTERIZING "PARTICIPATING" END-USE LOAD (NATIONAL, 2030)**

hourly load impacts of the modeled EE and demand flexibility measures, by summer and winter seasons, respectively.[78]

## Regional Variation in GEB Value

Regional differences occur due to variation in system costs, end-use saturations, building stock, and weather patterns, among other factors. Avoided energy cost is the primary source of value. **FIGURE 28** shows the total power system value estimated by region, and **FIGURE 29** shows the levelized value per megawatt-hour (MWh) of energy saved in each region.

A comparison of the results for California and Texas illustrates why the GEB value differs across regions. One MWh of EE and demand flexibility is more valuable in California than Texas, primarily because:

1. The EE and demand flexibility measures align better with CA's system peak, as demonstrated by the ratio of peak to average savings shown in Figure 36.

2. The marginal cost of capacity is higher in CA.

78 Summer is defined as June through September and winter is defined as December through March.

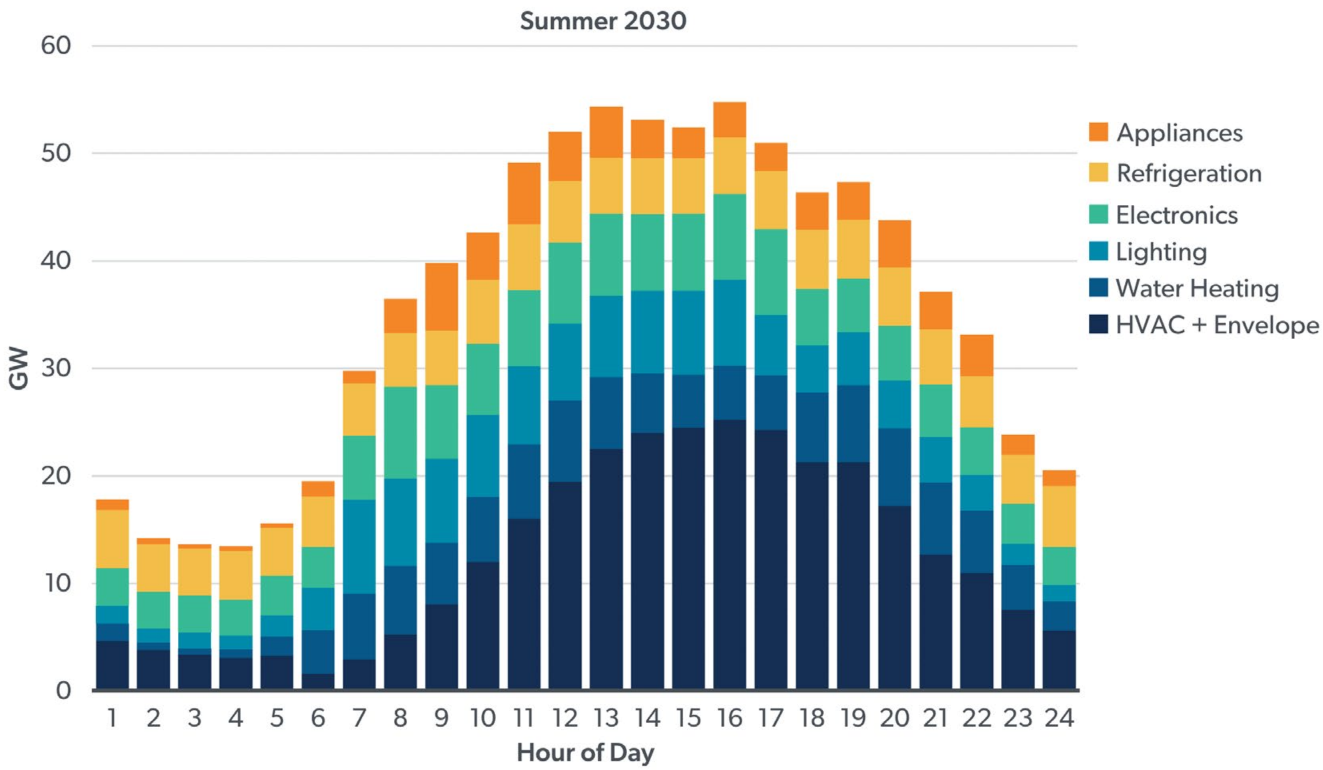



**FIGURE 26:** SUMMER 2030 – AVERAGE HOURLY PROFILE OF NATIONAL AGGREGATE SAVINGS

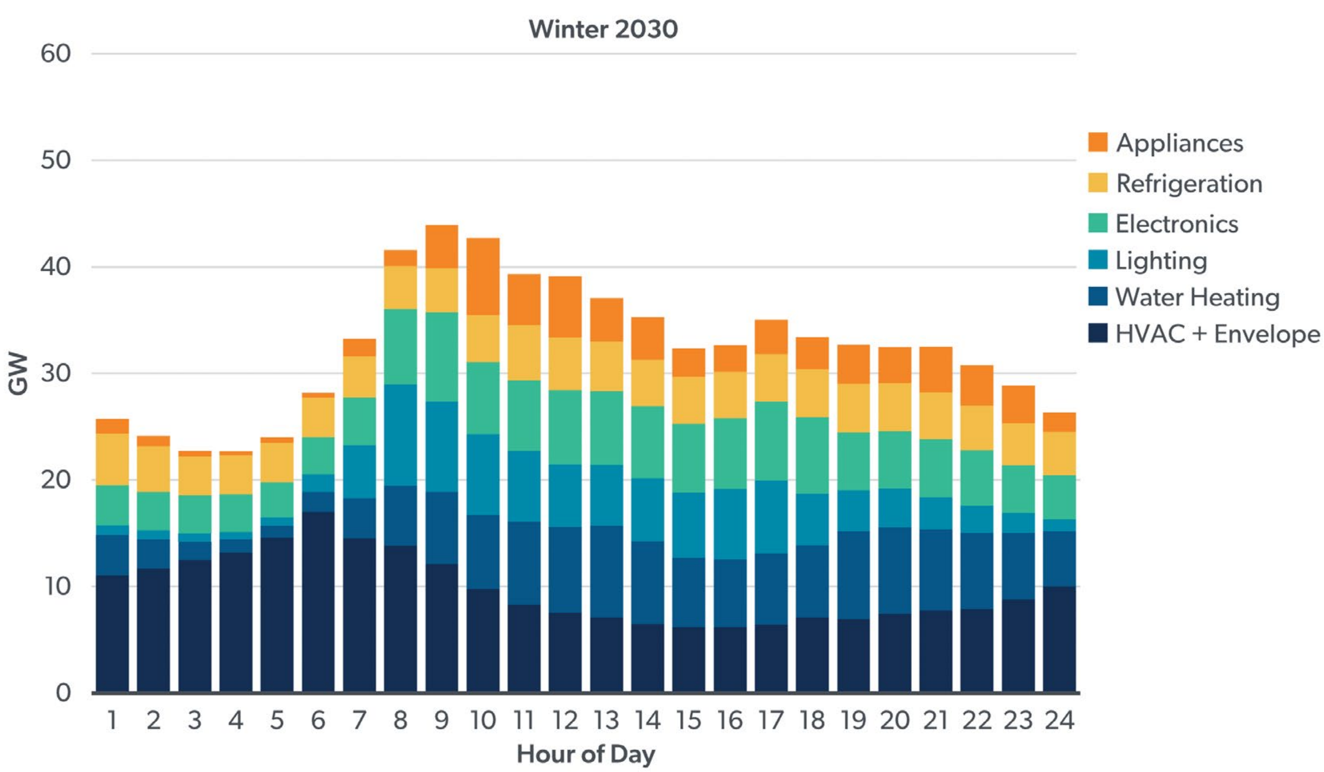



**FIGURE 27:** WINTER 2030 – AVERAGE HOURLY PROFILE OF NATIONAL AGGREGATE SAVINGS

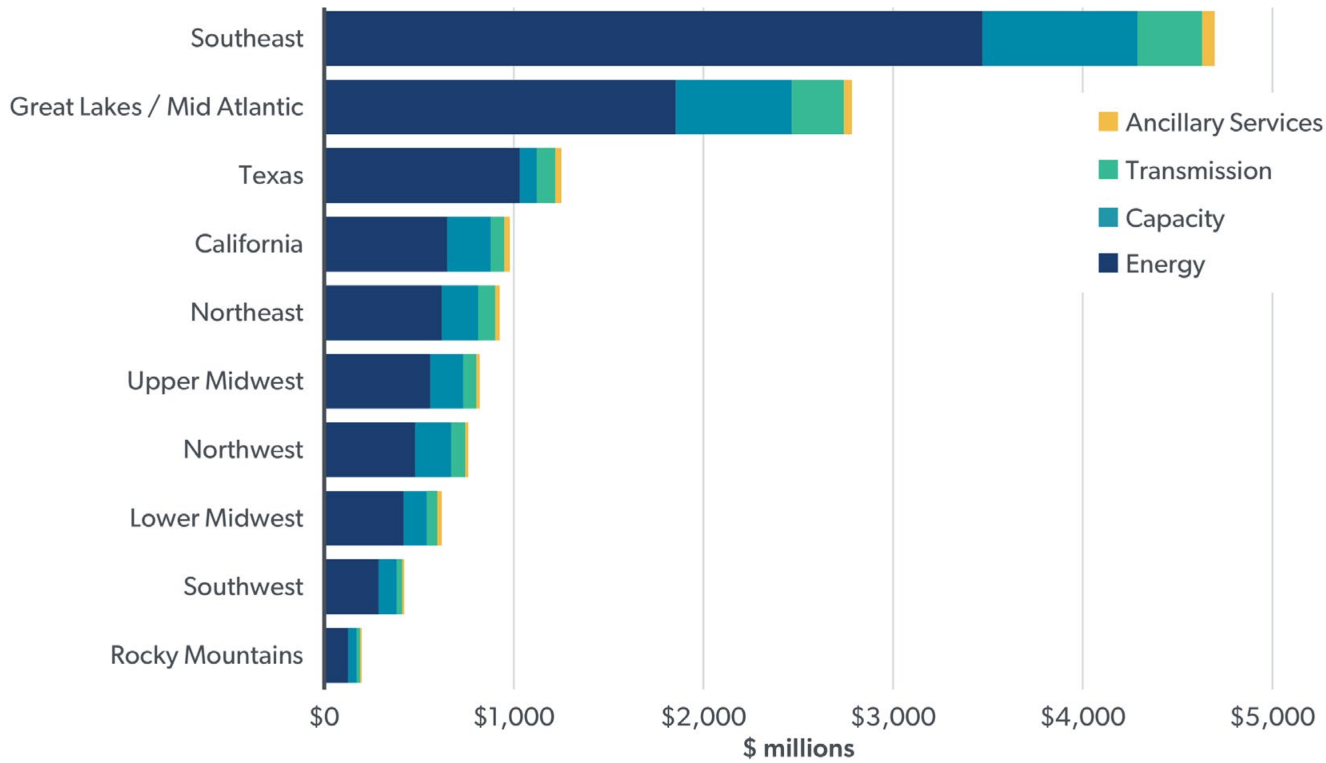



**FIGURE 28:** TOTAL VALUE OF EE+DF BY REGION (2030)

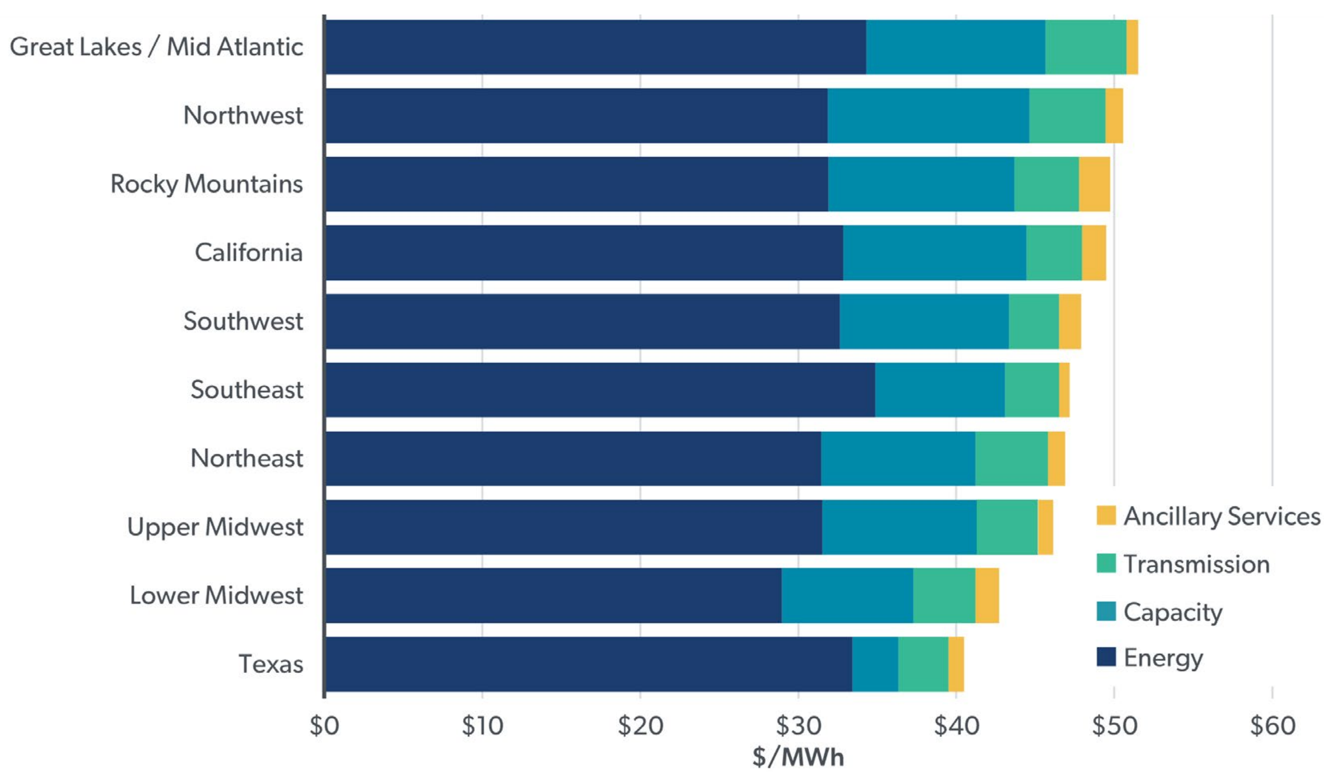



**FIGURE 29:** LEVELIZED VALUE OF EE+DF BY REGION (2030)

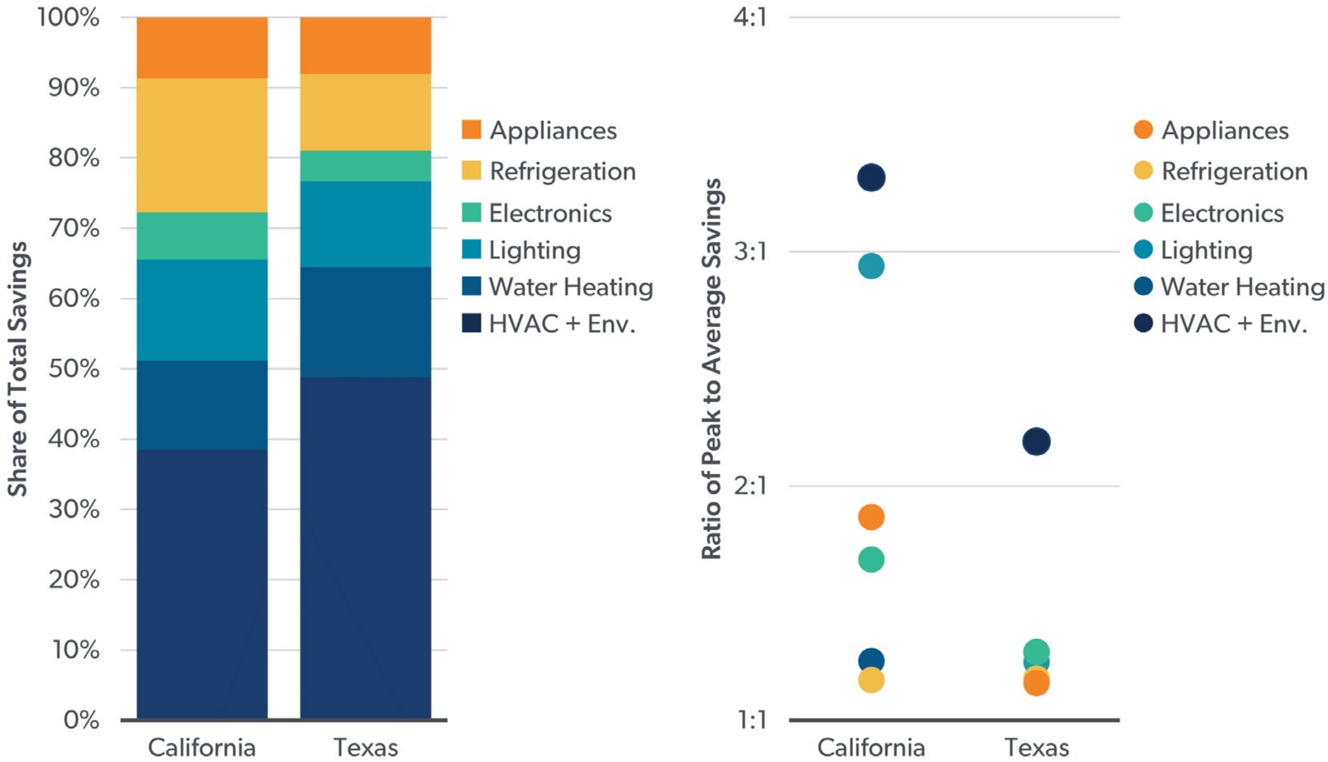



**FIGURE 30: ENERGY SAVINGS BY END-USE – CA VS. TX (2030)**

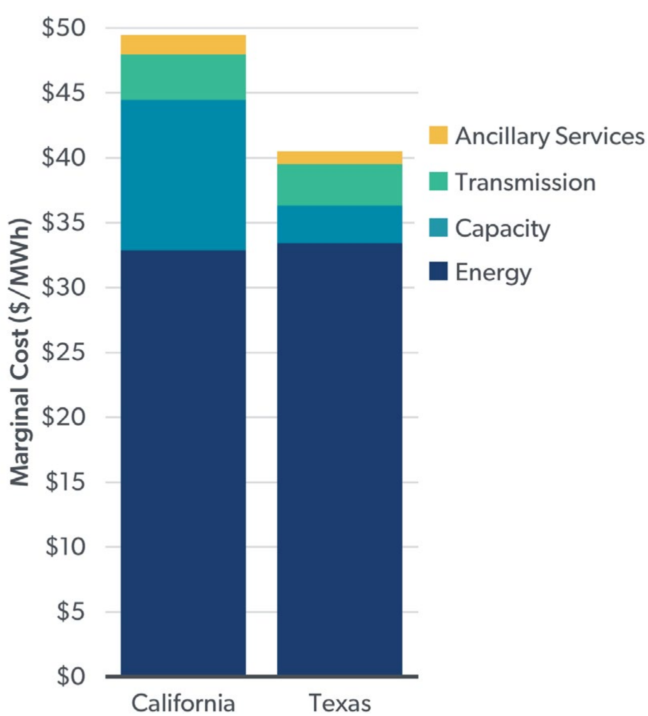



**FIGURE 31: AVERAGE MARGINAL COSTS – CA VS. TX (2030)**

However, value-per-MWh-saved is not the only relevant metric when comparing the relative value of EE and demand flexibility measures. In particular, measure benefits should be compared to technology and program costs in order to fully identify the most attractive opportunities.

## The Impact of Renewable Generation

With virtually no variable cost, renewable generation reduces marginal system energy costs by displacing higher-cost generators that otherwise would be operating on the margin (see **FIGURE 32**). This reduces the benefit of EE measures (-16%) because the opportunity for energy cost savings is lessened during the hours in which renewables have reduced marginal cost.[79] However, demand flexibility measure benefits increase (+3%); demand flexibility measures benefit from the greater price differential between mid-day hours and evening hours, due to their ability to shift load between those two periods.

79 As noted in Chapter 2, an additional benefit not captured in this analysis is the reduced cost of RPS compliance, since energy savings lessen the need for renewables procurements. Accounting for this benefit could offset some or potentially even all of the otherwise reduced energy cost savings, depending on the dynamics of the power system being analyzed.

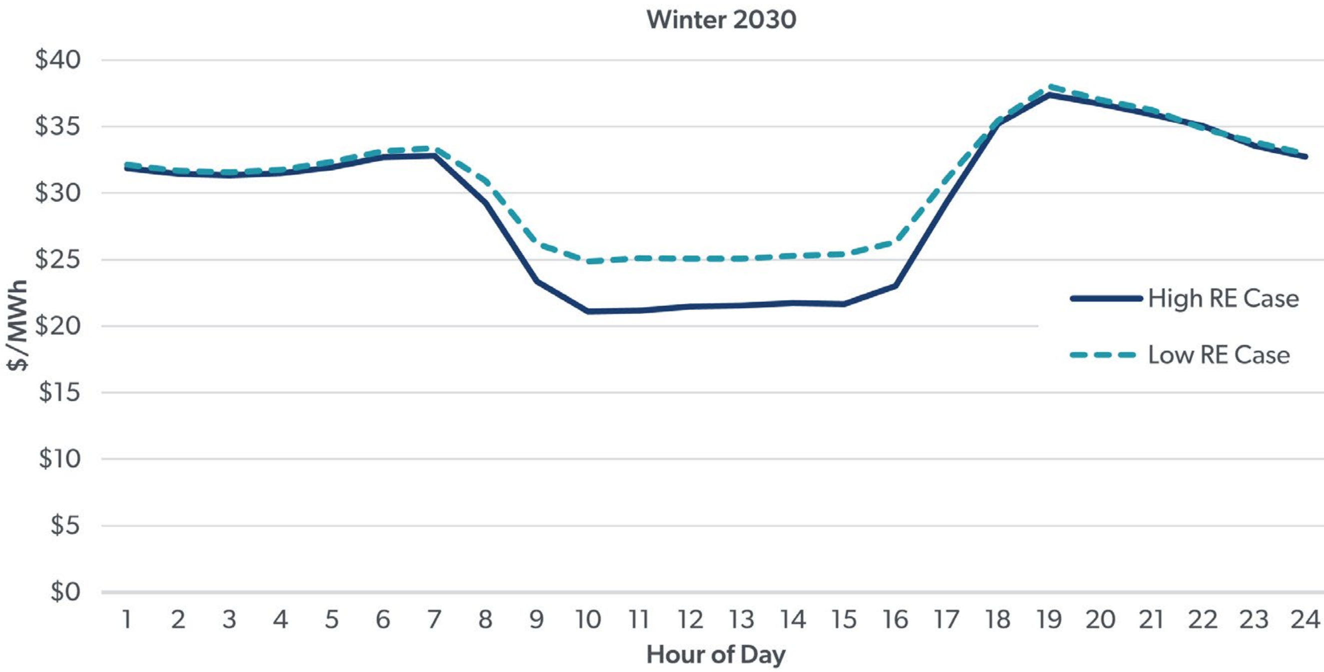



**FIGURE 32:** AVERAGE WINTER MARGINAL ENERGY COST IN CA (2030)

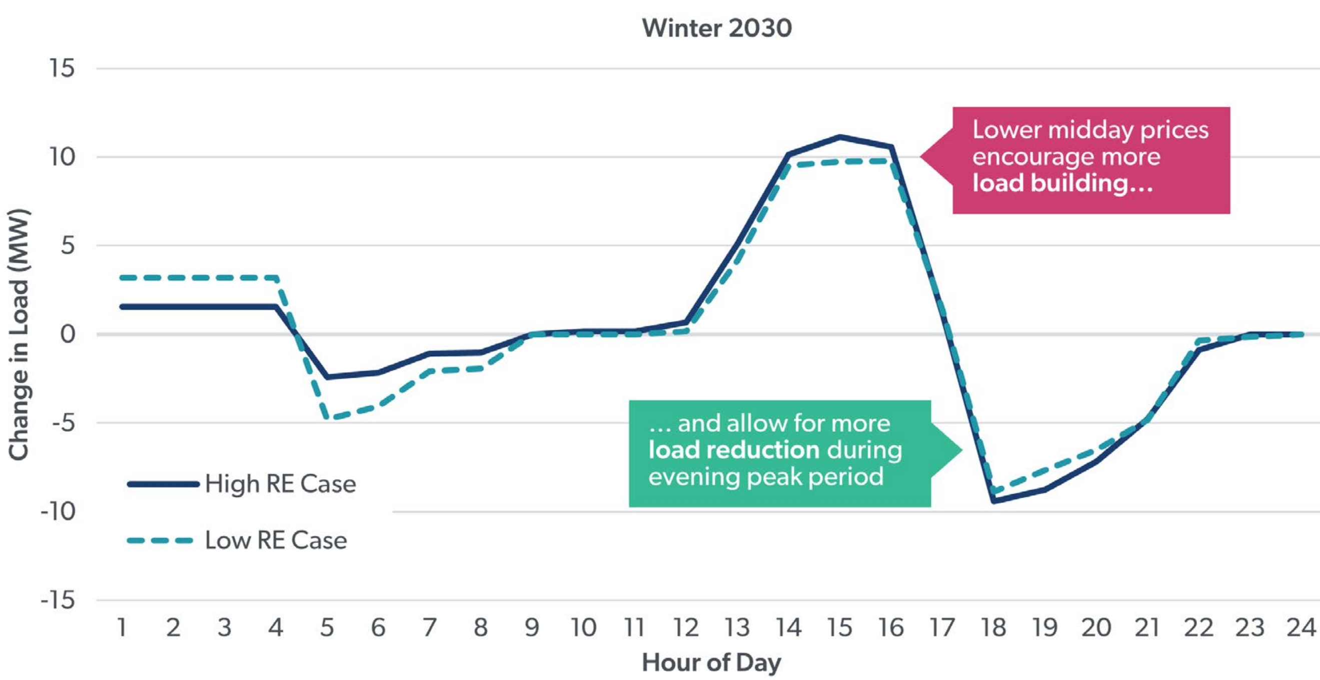



**FIGURE 33:** AVERAGE WINTER CHANGE IN LOAD FOR A RESIDENTIAL PRECONDITIONING (DF) MEASURE IN CALIFORNIA (2030)

## Savings Summary Tables

| Region | HVAC | Water Heating | Lighting | Electronics | Refrigeration | Appliances | Total |
|---|---|---|---|---|---|---|---|
| Southwest | 3,500 | 1,141 | 1,143 | 668 | 1,285 | 1,094 | 8,831 |
| California | 7,620 | 2,516 | 2,841 | 1,338 | 3,777 | 1,709 | 19,801 |
| Texas | 15,068 | 4,831 | 3,780 | 1,340 | 3,379 | 2,472 | 30,870 |
| Southeast | 43,105 | 19,430 | 12,579 | 4,350 | 12,495 | 7,593 | 99,551 |
| Upper Midwest | 6,207 | 2,939 | 2,509 | 1,275 | 2,660 | 2,204 | 17,794 |
| Northeast | 6,153 | 2,772 | 3,423 | 1,508 | 4,036 | 1,838 | 19,730 |
| Northwest | 5,543 | 2,261 | 1,934 | 1,173 | 2,446 | 1,693 | 15,049 |
| Lakes / Mid Atl. | 18,963 | 8,359 | 9,087 | 3,740 | 9,116 | 4,751 | 54,015 |
| Rocky Mountains | 1,589 | 483 | 559 | 280 | 599 | 458 | 3,968 |
| Lower Midwest | 6,398 | 2,322 | 1,858 | 746 | 1,791 | 1,394 | 14,509 |
| TOTAL | 114,145 | 47,053 | 39,712 | 16,417 | 41,584 | 25,205 | 284,117 |

**TABLE 10:** ENERGY SAVINGS BY REGION AND END USE IN 2030

| Region | HVAC | Water Heating | Lighting | Electronics | Refrigeration | Appliances | Total |
|---|---|---|---|---|---|---|---|
| Southwest | 1,218 | 194 | 173 | 111 | 175 | 161 | 2,031 |
| California | 2,883 | 359 | 953 | 257 | 505 | 364 | 5,322 |
| Texas | 3,766 | 712 | 538 | 197 | 454 | 327 | 5,995 |
| Southeast | 14,725 | 3,182 | 2,690 | 828 | 1,337 | 1,259 | 24,021 |
| Upper Midwest | 3,219 | 460 | 459 | 206 | 356 | 340 | 5,040 |
| Northeast | 4,121 | 532 | 883 | 217 | 539 | 362 | 6,654 |
| Northwest | 3,823 | 320 | 986 | 185 | 310 | 332 | 5,956 |
| Lakes / Mid Atl. | 11,396 | 1,446 | 2,151 | 524 | 1,203 | 893 | 17,612 |
| Rocky Mountains | 739 | 77 | 91 | 46 | 78 | 67 | 1,097 |
| Lower Midwest | 3,327 | 301 | 493 | 112 | 238 | 245 | 4,715 |
| TOTAL | 49,217 | 7,583 | 9,416 | 2,683 | 5,195 | 4,350 | 78,444 |

**TABLE 11:** PEAK DEMAND SAVINGS BY REGION AND END USE IN 2030

# Appendix C: Literature Review Findings

This appendix summarizes the findings of a review of the literature on barriers to GEB adoption and deployment. We reviewed 39 relevant reports, focusing on materials produced roughly within the past five years. Reviewed documents included several resources that were prepared by or in coordination with DOE, as well as resources produced by other organizations. DOE-related materials were provided to Brattle by DOE, while non-DOE materials were identified through internet research focused primarily on DR and load flexibility. The findings of this literature review are supplemented elsewhere in the *Roadmap* with insights from a stakeholder survey, stakeholder interviews, and meetings with technology experts from the National Labs.

## Barriers

| Group | Barrier Details | Source |
|---|---|---|
| Technology[80] | **Lack of energy management controls:** Just 12% of commercial buildings smaller than 25,000 $ft^2$, representing about a third of commercial floor space, had some kind of energy management control system for HVAC as of 2012, compared to more than 70% of U.S. commercial buildings larger than 100,000 $ft^2$. In the residential sector, Berkeley Lab estimates that some 10 million homes, roughly 8%, have connected smart thermostats. Residential AMI can complement device-level controls to monitor the performance of GEBs. | [6] Schwartz Leventis p. 13, [12] DOE p. 19 |
| Technology | **Lack of interoperability:** There are challenges in enabling seamless communication across devices within the home and between homes and the grid. In the home, challenges relate to proprietary device platforms (e.g., ACs and thermostats). Between the home and the grid, there is a need for well-developed DERMS (software platforms enabling centralized management of connected devices and DERs) and technologies that could enable transactive energy (in which participants buy/sell energy and ancillary services using automation tools). For commercial buildings which are managed by central EMIS systems, no universal standards exist for utilities or aggregators to connect to the building. | [1] AnnDyl, , [5] NEEP p. 34, [6] Schwartz Leventis p. 13, [12] DOE p. 19, [9] DOE, [22] ACEEE p. 12-13, [26] PNNL, [31] Cadmus p. viii |
| Technology | **Insufficient data access and granularity:** There is a need for open and secure data pathways between GEBs and wholesale markets, utilities, customers, third parties. There is a lack of granular data for accurate settlements (e.g., need at least hourly metering for wholesale markets), lack of real-time telemetry on distribution systems and DERs, and lack of consensus on the level of telemetry required (aggregation or device level). Data also can be a bottleneck for aggregators and third parties (with utilities sometimes unwilling to provide the data on the grounds of privacy or business strategy). It will be important to understand the right control node (device, end-use, zone, building) for demand flexibility and grid services. | [1] AnnDyl, [3] RMI-Synapse, [5] NEEP p. 32-33, [6] Schwartz Leventis p. 13, [12] DOE p. 19, [9] DOE, [18] NASEO, [22] ACEEE p. 13, [31] Cadmus p. viii, [34] Olivine p. 14 |
| Technology | **Privacy and cybersecurity concerns:** Real and perceived concerns about privacy and cybersecurity can limit adoption of GEBs and smart grid in general. There are more entry points for cyberattacks. Appropriate standards and protocols are needed to manage concerns about data use and privacy. There is a need to understand the trade-offs between functionality and cybersecurity. | [1] AnnDyl, [5] NEEP p. 33, [6] Schwartz Leventis p. 13/15, [12] DOE p. 19, [9] DOE |

80 For additional discussion of technology-related barriers, see Appendix E.

| Group | Barrier Details | Source |
|---|---|---|
| Technology | **Information barriers, analytical capabilities, and high costs:** Utilities lack info on proven technologies, equipment, and software, while manufacturers lack clarity from utilities on technology needs; utilities lack info on future R&D tech, while R&D organizations lack info on utility programs to steer R&D topics. Utilities often have limited "big data" analytical tools and capabilities, and may incur difficulties integrating DR with existing infrastructure and back-office systems.<br><br>Utilities report that some specific technologies needed for GEB deployment do not exist or are unproven, requiring stress-testing through pilot projects. A "siloed" deployment approach across DERs leads to high implementation costs from customized deployments. | [5] NEEP p. 32-33, [31] Cadmus p. viii |
| Technology | **Impact of demand flexibility on building and equipment durability:** Managing end-uses to provide demand flexibility could potentially strain building equipment and appliances that were not designed with that type of operation in mind. | [12] DOE p. 19 |
| Marketing and Participation | **Lack of customer knowledge about the value of DERs, confusion about DER objectives:** Consumers need to be educated about the value proposition of grid-connected and smart energy management tech to ensure adoption, optimal use, and participation in programs. There is a need for easy-to-use tools that help assess building load flexibility and grid services potential, and to understand how occupants respond to load flexibility technologies and other mechanisms for engaging occupants in activating demand.<br><br>For customers, efficiency and DR can seem to have diverse or conflicting objectives, and the difference between saving energy through efficiency measures and reducing demand at specific times can be confusing. Other customers may be concerned that efficiency will reduce their bill credits for shifting load during DR events. Enabling technologies such as AMI can add to this confusion if rollouts are delayed or subject to technical glitches. | [1] AnnDyl, [3] RMI-Synapse, [6] Schwartz Leventis p. 14, [12] DOE p. 19, [31] Cadmus p. viii, [35] ACEEE |
| Marketing and Participation | **Split incentives:** Builders may have little incentive to invest in advanced equipment and systems that enable demand flexibility, because subsequent owners or tenants will pay the energy bills and receive the benefits. Building owners have similar disincentives when tenants pay these bills. | [6] Schwartz Leventis p. 14, [14] NASEO |
| Regulatory and Policy | **Narrowly-focused and outdated policy goals:** Many EE policies narrowly target energy reduction (e.g., % savings). Those policies also could include year-round load management, demand reduction, demand intensity (W/sqft), energy costs, and emissions reductions. | [2] GSA GBAC, [5] NEEP p. 33 |

| Group | Barrier Details | Source |
|---|---|---|
| Regulatory and Policy | **Lack of integrated EM&V regulatory rules:** Conducting evaluation, measurement, and verification and/or determining the success of IDSM programs is challenging given that there are multiple programs and measures interacting with each other. No common approach to valuation has been adopted for programs that cross disciplines – often, programs require evaluation on a case-by-case basis. | [5] NEEP p. 33, [30] LBNL p. ix, 18 |
| Regulatory and Policy | **Potential not well characterized:** Assessments of the technical, economic, and achievable potential of demand flexibility (e.g., by market sector, operating mode, and grid services provided) are nascent. Such studies are needed for utility distribution and bulk power system planning, developing utility and state and local demand flexibility programs, and forecasting demand flexibility participation in RTO/ISO markets. | [6] Schwartz Leventis p. 14, [12] DOE p. 19, [9]-[13] DOE |
| Regulatory and Policy / Wholesale Market | **Lack of coordination between wholesale-retail-regulatory interface:** There are communication and coordination gaps between wholesale & retail operators (and costs associated with increased coordination), wholesale markets & retail programs, and wholesale markets & state regulators. There are varying perceptions of the risk of "double counting" when DERs participate in both wholesale markets and retail programs. Further, there are unclear regulatory and business models for aggregation and inter-building demand flexibility/energy exchange. Constraints exist on the ability of third-parties to aggregate DERs. | [3] RMI-Synapse, [12] DOE p. 19, [8] NASEO, [14] NASEO, [33] EDF p. 11, [34] Olivine p. 14 |
| Regulatory and Policy / Wholesale Market | **Outdated thinking by market participants and regulators:** Certain regulations restrict DER participation (e.g., some MISO states ban retail aggregation of DR). Lack of participation by DER providers in wholesale stakeholder processes can lead to domination by traditional incumbents. | [3] RMI-Synapse, [34] Olivine p. 14, [36] LBNL, et al. p. 7–21 |
| Wholesale Market | **Complex and/or restrictive market rules for DERs:** Dual participation is not allowed in some regions due to concerns of "double counting," limiting capture of multiple stacked value streams. Some models do not allow exports to the grid (e.g., CAISO Proxy Demand Resource), and some have participation caps (e.g., ERCOT ERS and ISO-NE RTR exemption). Market rules are often oriented toward the characteristics of traditional generators, which can be onerous for DERs (e.g., forward commitment in capacity markets, metering/telemetry, capacity accreditation). Interconnection agreements for DERs can be complex. | [3] RMI-Synapse, [6] Schwartz Leventis p. 15, [14] NASEO, [34] Olivine p. 23, [36] LBNL et al. p. 7–21 |
| Regulatory and Policy / Utility Planning and Implementation | **Incomplete cost-effectiveness testing:** Traditional cost-effectiveness screens can undervalue EE/DERs by missing the full cost of replacing supply-side infrastructure as well as non-energy benefits. In addition, there can be a lack of sufficient metrics for evaluating the cost-effectiveness of integrated DSM programs. | [1] AnnDyl, [14] NASEO, [30] LBNL p. ix, [31] Cadmus p. viii, [33] EDF p. 11 |

| Group | Barrier Details | Source |
|---|---|---|
| Regulatory and Policy / Utility Planning and Implementation | **Subpar performance metrics and assessment practices:** There is no standardized methodology for evaluating the economics of pilots and programs. Regulatory metrics are focused on energy reductions but do not always include carbon reductions. Metrics for state and local programs and policies, such as building energy ratings, building performance requirements, and EE targets, may require changes to better align with demand flexibility and the grid services it can provide. | [5] NEEP p. 33, [6] Schwartz Leventis p. 15, [14] NASEO, [30] LBNL p. ix, [31] Cadmus p. viii, [35] ACEEE |
| Regulatory and Policy / Utility Planning and Implementation | **Lack of price signals and efficient rate design:** Retail rates do not fully reflect the time and locational value of generating and delivering electricity. There is a need for alignment of rate design, incentives, and market compensation for demand flexibility with time-sensitive and locational value. | [1] AnnDyl, [5] NEEP p. 34, [6] Schwartz Leventis p. 15, [14] NASEO, [31] Cadmus p. viii, [32] FERC p. 40 |
| Regulatory and Policy / Utility Planning and Implementation | **Lack of integration in IRP, distribution, and transmission planning:** DERs are not always evaluated in utility planning processes on a level by playing field with traditional generation and grid infrastructure investments. Current planning models may not be able to capture all value streams from GEB technology (e.g., ancillary services) or non-energy benefits (e.g., resilience). | [1] AnnDyl, [5] NEEP p. 33, [6] Schwartz Leventis p. 15, [14] NASEO, [27] GridWise Alliance & EY p. 22 |
| Regulatory and Policy | **Lack of utility incentives:** Existing incentive structures may discourage the use of GEBs for utility (e.g., without decoupling, profits are tied to total sales, earning rate of return on infrastructure but not DER investments). | [1] AnnDyl, [6] Schwartz Leventis p. 15, [14] NASEO |
| Utility Planning and Implementation | **Lengthy procurement and program design processes for GEBs:** These delay progress and the development of innovative new approaches, making it difficult to stay on top of changing system needs and compete with conventional options when opportunities/needs arise. | [1] AnnDyl |
| Regulatory and Policy / Utility Planning and Implementation | **Lack of integrated DSM approach:** Utilities often "silo" EE, DR, and other DERs separately with different budgets, metrics, and evaluation methods, making it difficult to incentivize a combination of mutually supportive GEB strategies and adequately value measures providing both EE and load-shaping benefits. Often EE, DR, and DG programs compete for funding/administration; there is a need for "integrated" DSM but a lack of metrics sufficient for evaluating cost-effectiveness of integrated DSM. | [1] AnnDyl, [5] NEEP p. 33, [6] Schwartz Leventis, p. 14, [12] DOE p. 19, [14] NASEO, ACEEE p. 14, [30] LBNL p. ix, [31] Cadmus p. viii, [35] ACEEE |

| Group | Barrier Details | Source |
|---|---|---|
| **Utility Planning and Implementation** | **Competing priorities for human and financial resources.** Among utilities, new staff resources would be needed to develop and manage new programs. Among customers, staff would be needed to manage the program, in particular the day-to-day operations of responding to DR events. | [31] Cadmus p. viii |
| **Regulatory and Policy** | **Inability to trade DR resources across balancing authorities.** The contractual, legal, and administrative complexity of trading DR resources across balancing authorities can introduce additional costs. | [31] Cadmus p. viii |
| **Regulatory and Policy / Utility Planning and Implementation** | **Lack of established tariffs and contractual frameworks for DR.** | [31] Cadmus p. viii |
| **Marketing and Participation** | **Perceived lack of utility long-term commitment.** | [31] Cadmus p. viii |

## Literature Review References

The numbers below correspond to the numbers in the "source" column of the barriers table.


1. Saul Rinaldi, Kara, Elizabeth Bunnen, and Sabine Rogers. "Residential Grid-Interactive Efficient Building Technology and Policy: Harnessing the Power of Homes for a Clean, Affordable, Resilient Grid of the Future." Prepared for NASEO, October 2019.
2. Dutta, Projjal, Ralph DiNola, and Sonia Punjabi. "GSA Green Building Advisory Committee Federal Building & Grid Integration: Proposed Roadmap Advice Letter." Letter to Kevin Kampschroer, December 9, 2019.
3. Teixeira, Anthony, Doug Hurley, Natalie Mims Frick. "GEB Participation in Wholesale Markets." Internal Briefing for the U.S. DOE – Building Technologies Office, February 2020.
4. Southwest Energy Efficiency Project (SWEEP). "Grid-Interactive Efficient Buildings: Providing Energy Demand Flexibility for Utilities in the Southwest." Prepared by Justin Brant, August 2019.
5. Northeast Energy Efficiency Partnerships, Inc. "Grid-Interactive, Efficient Buildings (GEBs) Tri-Region Status Report." January 2020.
6. State and Local Energy Efficiency Action Network. "Grid-Interactive Efficient Buildings: An Introduction for State and Local Governments." Prepared by Lisa Schwartz and Greg Leventis, Lawrence Berkeley National Laboratory, April 2020.
7. State and Local Energy Efficiency Action Network. "Determining Utility System Value of Demand Flexibility from Grid-Interactive Efficient Buildings." Prepared by Tom Eckman, Lisa Schwartz, and Greg Leventis, Lawrence Berkeley National Laboratory, April 2020.
8. NASEO. "Grid-interactive Efficient Buildings: State Briefing Paper." October 2019.

9. U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Whole-Building Controls, Sensors, Modeling, and Analytics." Prepared by Amir Roth, December 2019.

10. U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Heating, Ventilation, and Air Conditioning (HVAC); Water Heating; Appliances; and Refrigeration." Prepared by Bill Goetzler, Matt Guernsey, and Theo Kassuga, December 2019.

11. U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Lighting and Electronics." Prepared by Valerie Nubbe and Mary Yamada, December 2019.

12. U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series –Overview of Research Challenges and Gaps." Prepared by Monica Neukomm, Valerie Nubbe, and Robert Fares, December 2019.

13. U.S. DOE. "Grid-interactive Efficient Buildings Technical Report Series – Windows and Opaque Envelope." Prepared by Chioke Harris, December 2019.

14. GEB Sunday Session Notes. "Meeting Summary of 9/15/19 NASEO Side Meeting on Grid-Interactive Efficient Buildings." 2019.

15. Mims Frick, Natalie. Lawrence Berkeley National Laboratory. Email Message to Monica Neukomm at DOE. "Re: FW: GEB side meeting at NASEO Annual Meeting – meeting notes attached." April 23, 2020.

16. "Grid Interactive Efficient Buildings Discussion 9.15.19-DRAFT." Agenda for the NASEO 2019 Annual Meeting, Manhattan Beach, CA, September 15, 2019.

17. U.S. DOE. "Grid-interactive Efficient Buildings." April 2019.

18. NASEO. "GEBs Barriers and Opportunities for NASEO Meetings 20190915." PowerPoint presentation, 2019.

19. NASEO. "NASEO-NARUC Grid-interactive Efficient Buildings Working Group." 2019.

20. Institute for Policy Integrity. "Getting the Value of Distributed Energy Resources Right – Using a Societal Value Stack." Prepared by Justin Gundlach and Burcin Unel, Ph.D., December 2019.

21. Rocky Mountain Institute. "Value Potential for Grid-Interactive Efficient Buildings in the GSA Portfolio: A Cost-Benefit Analysis." Prepared by Matt Jungclaus, Cara Carmichael, and Phil Keuhn, 2019.

22. ACEEE. "State of the Market: Grid-Interactive Efficient Building Utility Programs." Prepared by Christopher Perry, Hannah Bastian, and Dan York, October 2019.

23. Smart Electric Power Alliance. "Launching Plug and Play Distributed Energy Resources into the Future: Thinking Beyond Silos and Embracing Universal Technology Integration." Prepared by Steven Widergren, Pacific Northwest National Laboratory and Christine Stearn, Smart Electric Power Alliance, January 2020.

24. Smart Electric Power Alliance. "DERMS Requirements – Distributed Energy Resource Management System – Version 2.0." February 2019.

25. Regulatory Assistance Project. "Beneficial Electrification: Ensuring Electrification in the Public Interest." Prepared by D. Farnsworth, J. Shipley, J. Lazar, and N. Seidman, June 2018.

26. U.S. DOE. "Buildings Interoperability Landscape." Prepared by DB Hardin, EG Stephan, W Wang, CD Corbin, and SE Widergren, December 2015.

27. GridWise Alliance and EY Global Services Limited (EY). "In an Accelerated Energy Transition, Can US Utilities Fast-Track Transformation?" Prepared by Dana Hanson, Omar Al-Juburi, Jeff Miller, and Brad Hartnett, December 2019.

28. Regulatory Assistance Project. "The Next Quantum Leap

in Efficiency: 30 Percent Electric Savings in Ten Years." Prepared by Chris Neme and Jim Grevatt, February 2016.

29. Rocky Mountain Institute. "The Economics of Demand Flexibility: How 'Flexiwatts' Create Quantifiable Value for Customers and the Grid." Prepared by Mark Dyson, James Mandel, et al., August 2015.

30. Lawrence Berkeley National Laboratory. "Barriers and Opportunities to Broader Adoption of Integrated Demand Side Management at Electric Utilities – A Scoping Study." Prepared for the Office of Energy Efficiency and Renewable Energy U.S. DOE, February 2018.

31. The Cadmus Group. "Assessment of Barriers to Demand Response in the Northwest's Public Power Sector." Prepared by Haeri, Hossein, Karen Horkitz, Hanna Lee, Joan Wang, Trent Hardman, Hugh Ratcliffe, Masumi Izawa, Justin Brant, Jeremy Eckstein, Nina Preston, Lakin Garth, February 16, 2018.

32. Federal Energy Regulatory Commission. "2019 Demand Response and Advanced Metering." Prepared by Neil Chatterjee, Richard Glick, and Bernard McNamee, December 2019.

33. Environmental Defense Fund. "Putting Demand Response to Work for California." Prepared by Michael Panfil and James Fine, 2015.

34. Olivine, Inc. "Distributed Energy Resources Integration: Summarizing the Challenges and Barriers." Prepared by Robert W. Anderson, Spence Gerber, and Elizabeth Reid, January 24, 2014.

35. ACEEE. "Integrated Energy Efficiency and Demand Response Programs." Prepared by Dan York, Grace Relf, and Corri Waters, September 2019.

36. Lawrence Berkeley National Laboratory. "2025 California Demand Response Potential Study – Final Report on Phase 2 Results." Prepared by the Lawrence Berkeley National Laboratory, Energy and Environmental Economics, Inc. (E3), and Nexant, Inc., March 1, 2017.

37. Good, Nicholas, Keith A. Ellis, and Pierluigi Mancarella. "Review and classification of barriers and enablers of demand response in the smart grid." *Renewable and Sustainable Energy Reviews*, 72, 2017, pp. 57-72.

38. Parrish, Bryony, Phil Heptonstall, Rob Gross, Benjamin K. Sovacool. "A systematic review of motivations, enablers and barriers for consumer engagement with residential demand response." *Energy Policy*, Volume 138, March 2020.

39. Cardoso, Catarina Araya, Jacopo Torriti, Mate Lorincz. "Making demand side response happen: A review of barriers in commercial and public organisations." *Energy Research & Social Science,* Volume 64, June 2020.

# Appendix D: Stakeholder Engagement Details

**The discussion of GEB barriers and recommendations in this *Roadmap* was informed in part by two stakeholder engagement activities: A survey of 75 industry stakeholders and interviews with experts from over 25 industry organizations. This appendix summarizes the methodology behind those activities.**

## Stakeholder Survey

The stakeholder survey was administered electronically using SurveyMonkey. We received 75 responses from approximately 125 invitees (a 60% response rate). Invitees were selected to span a broad range of demand flexibility stakeholder groups, with a focus on individuals considered by the *Roadmap* authors to have substantial expertise in this area. Invitations were deliberately weighted toward organizations with implementation responsibility (e.g., utilities, aggregators) due to their involvement and visibility across the GEB value chain. The mix of survey respondents is summarized in **FIGURE 34**.

After being provided a brief overview of the research goals and being asked questions about their background, survey respondents were asked to respond to the following questions related to demand flexibility barriers, and potential options for addressing the barriers.

### Barriers to Load Flexibility Deployment

The following are commonly cited barriers to load flexibility deployment. To the extent that there is untapped potential in load flexibility, what are the top 5 barriers to realizing that potential? Please rank your top 5 choices, with a “1” representing the most important barrier to overcome, a “2” representing the second most important barrier, etc.

- Lack of market-ready building automation technology
- Cost and/or complexity of building automation technology
- Insufficient savings opportunities for building owners
- Insufficient supporting infrastructure (e.g., lack of advanced metering infrastructure)
- Privacy and cybersecurity concerns of customers/ building owners

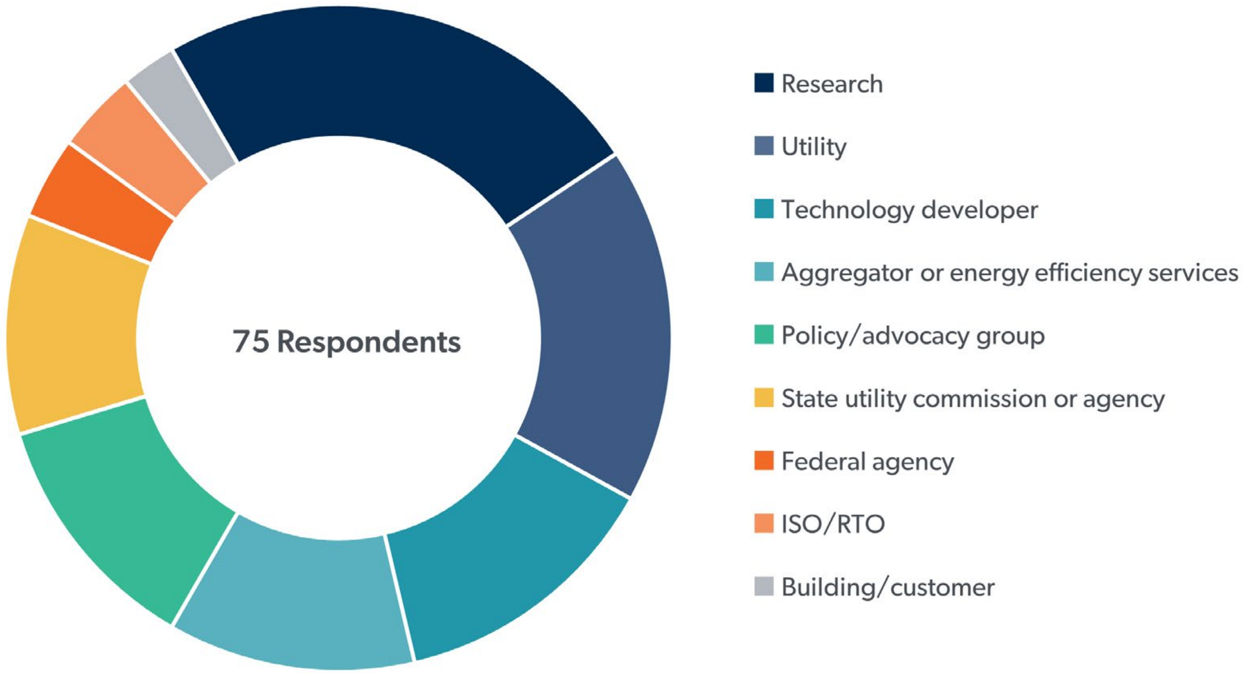



**FIGURE 34: COMPOSITION OF SURVEY RESPONDENTS**

- Lack of customer/building owner interest or awareness
- Lack of understanding by the entities responsible for implementing load flexibility offerings (including both installers and end-users)
- Lack of financial incentive for utility to pursue load flexibility
- Program design that makes load flexibility unattractive to potential participants
- Insufficient customer incentive structure (incl. lack of retail rate designs that encourage load flexibility)
- Limitations on ability of third parties (aggregators/ESCOs) to participate/compete
- "Status quo bias" – including institutional bias against demand-side solutions among utilities as well as reluctance of building operators to alter systems
- Load flexibility not sufficiently represented in utility resource planning processes
- Wholesale market designs that do not fully compensate load flexibility for its value
- Complex or unnecessarily restrictive wholesale market participation rules
- Insufficient load flexibility performance metrics and assessment practices (e.g., EM&V)
- Inability to monetize the full "value stack" of load flexibility (i.e., combining distribution-level benefits with bulk system-level benefits)

## Additional Barriers

Have we missed any important barriers? If so, please describe them in the comment box below and indicate where they would rank in the list of the top 5 barriers you identified previously (if applicable).

## Organizations Best Equipped to Address the Barriers

What are the top 3 organizations with the most important role to play in overcoming the barriers to load flexibility deployment? Please rank your top 3 choices, with a "1" representing the most important organization, a "2" representing the second most important organization, etc.

- Utilities
- Third-party aggregators or ESCOs
- State regulators
- Other state government agency
- Federal government
- ISO/RTO
- Research organizations
- Customers, building owners, or managers
- Building equipment installers
- Technology developers/service providers
- EE, DR, or environmental policy/advocacy groups

## Solutions for Overcoming the Barriers

Now that we've reviewed the barriers to load flexibility deployment, we'll move on to solutions for overcoming the barriers. On a scale of 1 to 5, please indicate both the feasibility and likely effectiveness of each solution shown in **TABLE 12**. A "1" indicates that the solution is highly feasible or effective. A "5" indicates that the solution is infeasible or very unlikely to be effective.

## Additional solutions

Are there any important solutions that were not included in the previous list? If so, please describe them in the comment box below, and provide scores for feasibility and effectiveness on the same scale from 1 to 5.

## Case studies highlighting success and innovations

We are compiling a library of case studies that illustrate successful or innovative approaches to overcoming barriers to load flexibility deployment, with a focus on approaches that could have broad applicability.

| Category | Solution Option |
|---|---|
| Research | Research studies (e.g., market research on consumer preferences, market potential studies, best practices documents, scientific pilots, building technology demonstration projects, measurement, and verification of building system performance)<br><br>R&D funding for the development of building load flexibility technologies and systems (e.g., to scale new technologies, reduce cost, and increase ease of installation/usability)<br><br>Enhanced training for all levels of the implementation chain (e.g., workforce training among installers, designers, and other market actors)<br><br>Public models/tools (e.g., for evaluating load flexibility opportunities, or for building system design/optimization) |
| Implementation | Innovative load flexibility program design (e.g., packaging load flexibility with other offers)<br><br>New retail rate design (e.g., location-specific and/or time-varying pricing)<br><br>Enhanced customer marketing and outreach (e.g., AMI-based targeted marketing)<br><br>Modernization of existing conventional DR programs |
| Governmental Action (Legislative or Regulatory) | Comprehensive and transparent EM&V and cost-effectiveness protocols<br><br>Requirement that load flexibility be represented in resource planning processes such that its full value proposition is accounted for<br><br>Financial incentives for utilities<br><br>Enablement of third-party (aggregator) participation/competition<br><br>Codes & standards for buildings or technologies (e.g., controls standards supporting interoperability, building and appliance standards to promote load flexibility)<br><br>Load flexibility goals or mandates (also could be achieved through legislation) |
| Wholesale Market Design | Establishment of wholesale market products and participation rules that are clear and fully compensate load flexibility for its value |
| Other | Create or assign responsibility for an organization – or coalition of organizations – specifically to drive load flexibility progress at the state level |

**TABLE 12: SOLUTION OPTIONS PRESENTED IN STAKEHOLDER SURVEY**

## Survey Results

Top barriers to demand flexibility deployment, as identified by the survey respondents, are summarized in **TABLE 13**. Respondents each were asked to select five barriers. Respondents expressed a range of views regarding the likely effectiveness and feasibility of each option for overcoming the barriers. **FIGURE 35** summarizes the unweighted average results across all survey respondents. As noted above, respondents were asked to rate the feasibility and likely impact of each option, using a "low, medium, high" scale. We assigned scores of 5 for high, 3 for medium, and 1 for low. Options in the top-right corner of the chart are perceived to have the highest feasibility and potential impact by the respondents.

| Response | Votes |
|---|---|
| Insufficient customer incentive structure (incl. lack of retail rate designs that encourage load flexibility) | 42 |
| Lack of customer / building owner interest or awareness | 38 |
| Inability to monetize the full "value stack" of load flexibility (i.e., combining distribution-level benefits with bulk system-level benefits) | 36 |
| Lack of financial incentive for utility to pursue load flexibility | 29 |
| "Status quo bias," including institutional bias against DF solutions among utilities and reluctance of building operators to alter systems | 28 |
| Cost and/or complexity of building automation technology | 25 |
| Load flexibility not sufficiently represented in utility resource planning processes | 24 |
| Insufficient savings opportunities for building owners | 22 |
| Lack of understanding by the entities responsible for implementing load flexibility offerings (incl. both installers and end-users) | 17 |
| Program design that makes load flexibility unattractive to potential participants | 15 |
| Wholesale market designs that do not fully compensate load flexibility for its value | 15 |
| Complex or unnecessarily restrictive wholesale market participation rules | 11 |
| Insufficient supporting infrastructure (e.g., lack of Advanced Metering Infrastructure) | 10 |
| Insufficient load flexibility performance metrics and assessment practices (i.e., EM&V) | 10 |
| Limitations on ability of third parties (aggregators/ESCOs) to compete with utilities | 10 |
| Lack of market-ready building automation technology | 10 |
| Privacy and cybersecurity concerns of customers / building owners | 8 |

**TABLE 13: TOP DF BARRIERS, AS IDENTIFIED BY SURVEY RESPONDENTS**

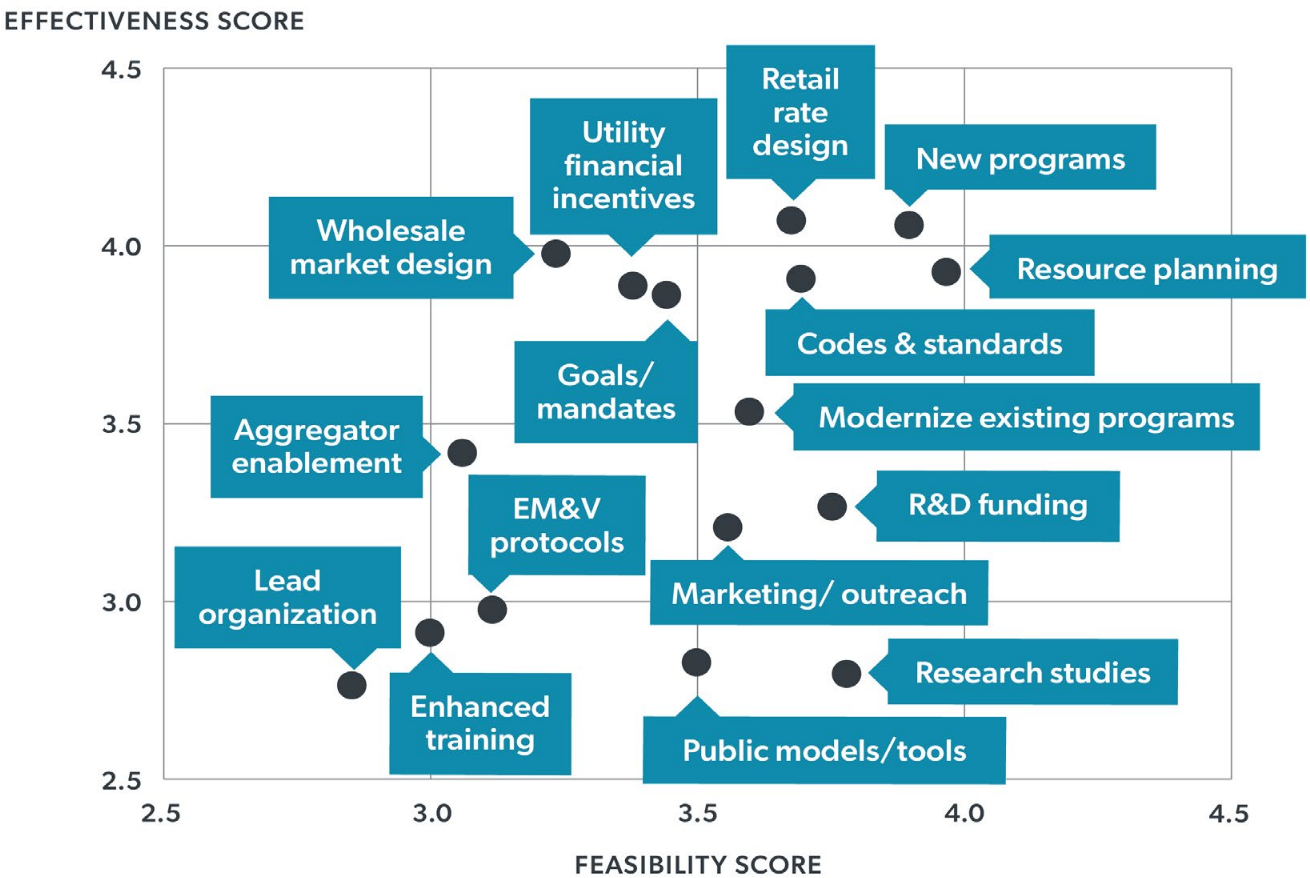



**FIGURE 35: PERCEIVED EFFECTIVENESS AND FEASIBILITY OF THE OPTIONS BY SURVEY RESPONDENTS**

## Expert Interviews

The *Roadmap* authors conducted in-depth interviews with individuals selected based on their deep expertise in demand flexibility matters, and their ability to provide a range of important perspectives on the issues. The interviews were conducted by phone or videoconference with individuals or small groups from the following organizations:

- ACEEE
- Austin Energy
- Atelier Ten
- Better Buildings Initiative, GEB working group
- Building Performance Association
- CA Efficiency + Demand Management CouncilCadeo Group
- Consortium for Energy Efficiency
- East River Electric
- Enel X
- ERCOT
- Federal Energy Regulatory Commission (FERC)
- Google Nest
- Johnson Controls
- Minnesota PUC
- National Association of Energy Service Companies
- National Association of State Energy Officials (NASEO)
- National Rural Electric Cooperative Association (NRECA)
- Natural Resources Defense Council (NRDC)
- North Carolina Electric Membership Corporation (NCEMCS)
- Peak Load Management Alliance
- Rocky Mountain Institute (RMI)
- Southern California Edison
- Uplight
- US Green Building Council
- Voltus
- Xcel Energy

Interviews were conducted as an open discussion structured around the following questions:

1. The demand flexibility opportunity
   a. Does demand flexibility have an important role to play in the future of the U.S. power system?
   b. If so, what are the most important short-term and long-term demand flexibility opportunities?
2. Prioritizing barriers to demand flexibility adoption and deployment
   c. What are the biggest barriers?
   d. Which stakeholders in the demand flexibility value chain face the biggest challenges to greater demand flexibility deployment/adoption?
   e. Do some barriers need to be addressed sooner than others? Which ones and why?
3. Options for addressing the barriers
   f. What are the most attractive options for addressing the barriers, and why?
   g. Why aren't these options already implemented? What needs to happen to implement those solutions?
   h. Who should lead the implementation of the solutions?
   i. What can reasonably be accomplished in the next two years? 10 years?
   j. What are some case studies, both in the U.S. and abroad, that highlight success in implementing the solutions?
4. Conclusion
   k. In your opinion, how can we ensure that the *Roadmap* will be used by stakeholders and have an impact?

# Appendix E: Additional Detail on GEB Technologies

This appendix provides additional detail about GEB technologies and the development of tables and figures in Chapter 3. Three primary information sources were utilized for the GEB technology descriptions and Chapter 3 discussion:

1. First, we reviewed and summarized four DOE GEB Technical Reports (Technical Reports) that provided a foundation to describe the capabilities of relevant GEB technologies.
2. Second, we organized a series of workshops with National Lab experts and Technology Managers from the DOE Building Technologies Office. These workshops included review and feedback on the Technical Reports as well as facilitated discussions to develop content on priority topics for Chapter 3.
3. Third, we administered a survey to prioritize the GEB technologies identified in both the GEB Technical Reports and the expert workshops to identify the most important opportunities for GEB technology research, development, and deployment.

This appendix supplements and details the concepts presented in Chapter 3 and should not be treated as a stand-alone document. For more detail, particularly on the GEB technologies discussed here and in Chapter 3, please refer to the Technical Reports.[81]

The remaining sections of the appendix discuss each primary information source. Specifically, the sections below: **(1)** summarize the GEB Technical Reports; **(2)** elaborate on the expert workshops with key outcomes; and **(3)** describe the methodology and results of a survey for identifying key GEB technologies.

## GEB Technology Report Summaries

The DOE Building Technologies Office (BTO) published a series of technical reports that evaluate the opportunities and challenges for GEBs. The reports include an overview report and four Technical Reports that evaluate state-of-the-art and emerging building technologies: *HVAC, Water Heating, Appliances, and Refrigeration; Lighting and Electronics; Windows and Opaque Envelope; and Whole-Building Controls, Sensors, Modeling, and Analytics*.

The main purpose of the Technical Reports was to rate the technologies on their ability to provide grid services (e.g., efficiency, load shed, load shift, load modulation). These ratings are qualitative and based on estimated theoretical technical potential based on current research studies and expert guidance. Importantly, the ratings are not informed by technical potential quantified in Chapter 2, which assumes

81 The GEB Technical Reports are available here: https://www.energy.gov/eere/buildings/grid-interactive-efficient-buildings

specific energy efficiency and demand flexibility measure performance levels. No lab testing or experimental pilot tests were performed as part of this evaluation. In addition, each grid service was weighted based on the opportunity space in the building sector. Building technologies can provide significant value to the grid through energy efficiency and peak demand reductions based on the current market size of key building end uses. The Technical Reports also examined the need for various grid services. Therefore, the ability to perform efficiency, shedding, and shifting was weighted higher than modulating loads. Based on the ability to provide each grid service, the number of strategies provided, and the weighting of each grid service, each technology is determined to have low, medium, or high potential to provide grid services.

The Technical Report summaries below are divided into two sub-sections: **1)** a summary of the three end-use specific Technical Reports (HVAC, Water Heating, Appliances, and Refrigeration; Lighting and Electronics; and Windows and Opaque Envelope); and **2)** a summary of the Whole-Building Controls, Sensors, Modeling, and Analytics report. For each Technical Report summary, we first describe the scope and impact. We then present a technology evaluation and the potential for demand flexibility. Last, we describe the technical challenges of and R&D opportunities for the individual technologies.

## End-use Technology Report Summaries

### HVAC, Water Heating, Appliances, and Refrigeration Technical Report Summary

This report focuses on HVAC, water heating, appliances, and refrigeration, as well as related cross-cutting equipment. As part of the appliance discussion, this report includes miscellaneous electric loads (MELs) that relate to HVAC, water heating, appliances, and refrigeration. Embedded controls and accessories, including smart thermostats, are also included, whereas on-site building-level controls (e.g., building management system/BAS/BEMS and SHEMS) and off-site devices and controls are beyond the scope of this report. This report excludes technologies that only provide efficiency or other value, but no grid-flexibility capabilities in response to grid needs, such as tankless water heaters and self-powered natural gas equipment. This report does not contain a discussion of specific GEB ventilation technologies because ventilation flexibility is either provided by an integrated HVAC solution (e.g., a rooftop unit) or via sensors and controls systems.

#### *HVAC*

Air conditioning and space heating are the largest single contributors to summer and winter demand peaks both in buildings and for the electric grid systemwide, respectively. The duration over which the HVAC's electric demand can be reduced depends on the envelope design and thermal inertia of the building. Buildings that employ well-designed and maintained envelopes with high-performance windows, and insulation, and low outside-air infiltration can maintain comfortable indoor conditions for longer without operating the cooling equipment. All buildings must maintain acceptable air quality through the ventilation system, even during load shedding or shifting. Maintaining air quality is a standard function of HVAC systems in commercial buildings, but only an emerging consideration for residential buildings where ventilation is installed for new, tight-envelope homes. For older homes, envelopes are leakier and generally assumed to have sufficient air changes per hour. Therefore, older homes do not have mechanical ventilation requirements. HVAC demand flexibility and associated value to the grid varies by climate, driven to a great extent by weather consistency and long-term predictability. **TABLE 13** summarizes the relevant HVAC technologies identified in the Technical Reports.

| Technology | Definition | DF Potential |
|---|---|---|
| **Smart Thermostats** | Smart thermostats sense the temperature conditions inside a building and control the attached HVAC equipment to maintain the target conditions to maintain thermal comfort. | High |
| **Separate Sensible and Latent Space Conditioning** | Membrane dehumidifiers, liquid, and solid desiccants, and other air conditioning system components can remove moisture from supply air without changing its temperature (latent heat) while independently coordinating with a temperature-only (sensible) cooling stage, which enables independent control of sensible and latent cooling. | High |
| **Liquid Desiccant Thermal Storage** | Storage of liquid desiccants for dehumidification in separate sensible and latent HVAC systems provides flexibility for latent load management only during cooling season. | High |
| **Advanced Controls for HVAC Equipment with Embedded Thermostats** | HVAC equipment with embedded thermostats includes all necessary sensors and control algorithms built into the equipment itself or accessed by the equipment itself via a built-in communications device. This equipment category includes room air conditioners (A/Cs), portable A/Cs, packaged terminal A/Cs, conventional heat pumps, and ductless mini-split heat pumps. | Medium |
| **Hybrid Evaporative Precooling** | Packaged hybrid (evaporative and vapor-compression) cooling systems are designed to limit water consumption while maintaining a high cooling efficiency. They use sensors to monitor and analyze outdoor weather conditions, controls to determine which cooling method to operate, and employ various control strategies. | Low |
| **Dual-Fuel HVAC Systems** (electric or natural gas) | A dual-fuel HVAC system can provide demand reduction by temporarily switching fuels from electric to some other fuel during times of grid need. | Low |
| **Heat Pumps** | Heat pumps use electricity to move heat from a cool space to a warm space, making the cool space cooler and the warm space warmer. During the heating season, heat pumps move heat from the cool outdoors into the building. During the cooling season, heat pumps move heat from inside the building to the outdoors. | High |
| **HVAC and Hot Water Combo Systems** | Combination space/water heaters efficiently heat water and provide space heating. There are three basic configurations: 1) Indirect space heating: systems that heat water for domestic use and circulate hot water through a finned-tube coil, which transfers heat to air that is blown over the coil, 2) Indirect water heating: systems that heat water for space heating and either utilize a heat exchanger in the boiler to heat domestic water or redirect the flow of heated water through the domestic hot water storage tank as necessary, 3) Integrated heat pump systems that provide space heating, space cooling, and domestic hot water together or independently. | High |

**TABLE 13: STATE-OF-THE-ART GEB HVAC TECHNOLOGIES**

| Technology | Definition | DF Potential |
|---|---|---|
| **Water Heaters with Smart, Connected Controls** | Advanced water heater controllers can provide multiple forms of value to the grid by leveraging the water heater's energy storage capabilities, depending on the algorithm that is implemented. Examples include preheating during off-peak periods (load shifting), load shedding for emergency curtailment by shutting down the unit during emergency events to mitigate grid stress, and frequency regulation. | High |
| **Dual-Fuel Water Heater** | A dual-fuel water heater system can provide curtailment by temporarily switching fuels from electric to some other fuel during times of grid need. | Low |
| **Heat Pump Water Heater (HPWH)** | An HPWH takes the heat from surrounding air and transfers it to water in an enclosed tank. During periods of high hot water demand, HPWHs switch to standard electric resistance heat automatically. HPWHs come with control panels that allow the selection of different operating modes. | High |

**TABLE 14: STATE-OF-THE-ART GEB WATER HEATING TECHNOLOGIES**

| Technology | Definition | DF Potential |
|---|---|---|
| **Modulating, Advanced Clothes Dryer** | Clothes dryers can be designed to run at lower power or lower temperature by modulating or staging the heating cycle through simple controls for reduced energy use and better efficiency. | Medium |
| **Advanced Dishwasher/ Clothes Washer Controls** | Advanced dishwasher/clothes washer controls can enable grid-interactive operation with minimal impact on customer usability by delaying the start of their cycle until off-peak periods or until a utility-signal is received. | Medium |
| **Advanced Refrigerator/ Freezer Controls** | Advanced refrigerator controls can enable grid-friendly operation with little to no impact on customer usability. Examples include low-operation modes, defrost cycle delay, and freezer precooling. | Medium |
| **Refrigeration Appliances** | Examples include laboratory refrigerators and freezers, coolers, and cooler-refrigeration combination products. | Medium |
| **HVAC Equipment** | Examples include dehumidifiers, ceiling fans, furnace fans, and kitchen ventilation. | Medium |
| **Water Heating Appliances** | Examples include portable electric spas and pool heaters. | High |
| **Water Circulation Appliances** | Examples include pool pumps, boiler pumps, condensate drainage pumps, and spa/hot tub. | Medium |
| **Motors driven appliances** | Examples include fans, pumps, small kitchen appliances, and refrigeration. These appliances can be controlled through their built-in or externally attached controls. | Medium |
| **TES in Refrigeration** | Integrating thermal storage with frozen and refrigerated food can enable demand flexibility in refrigeration systems. The TES integration could be in addition to the advanced controls described earlier in the table. | High |

**TABLE 15: STATE-OF-THE-ART GEB APPLIANCE AND MELS TECHNOLOGIES**

| Technology | Definition | DF Potential |
|---|---|---|
| **Building-Scale CHP** | Using natural gas or other fuel sources, CHP systems capture wasted heat from the electricity generation system (e.g., engine, turbine, fuel cell) to satisfy space, water, and process heating loads. | High |

**TABLE 16: STATE-OF-THE-ART GEB NATURAL GAS TECHNOLOGIES**

| Technology | Definition | DF Potential |
|---|---|---|
| **Modulating Capacity Vapor Compression** | Modulating equipment in vapor compression systems (including A/Cs, heat pumps, dehumidifiers, HPWHs, and heat pump dryers) operate continuously at low speeds versus on/off at full capacity, which enables greater value to the grid because of the greater precision of controls it affords and increased efficiency. | Medium |
| **Non-Vapor-Compression (NVC) Materials and Systems** | NVC technologies are a series of space cooling and refrigeration systems that use unique properties of specialized materials or alternative system designs to the traditional vapor-compression cycle. Solid-state NVC technologies produce useful temperature differences based on the intrinsic material properties of their core solid-state substance when activated by electrical input. Other NVC technologies use electrical or thermal input to alter the phase or other properties of a working fluid or material to pump and move heat. NVC technologies can offer grid-interactivity benefits through modulating capacity, separate sensible and latent cooling, and energy storage capabilities. | High |
| **Thermal Energy Storage (TES)** | The TES medium can be regenerated during nonpeak hours, stored, and then discharged at any point throughout the day for daily load shedding. With appropriate controls, TES can be used more strategically in other behavioral, price-driven demand flexibility scenarios or for emergency/economic DR. TES is also valuable for applications where temperatures must be maintained precisely, which would disqualify precooling as an option. | High |
| **District Energy TES** | TES systems are often incorporated in residential and commercial districts or campus-level heating and cooling systems. For example, many campuses have chilled water tanks for off-peak storage. | High |

**TABLE 17: STATE-OF-THE-ART GEB CROSS-CUTTING TECHNOLOGIES**

### *Water Heaters*

Storage (e.g., tank-based) water heaters can provide value to the grid because of their ability to store thermal energy, enabling them to decouple power demand from end-use consumption. Thermal storage is built into the equipment by design, unlike in the case of tankless water heaters. Storage water heaters can be controlled to shift demand away from peak times while still providing the same function to consumers. Residential water heaters see the highest demand during daily morning and evening peaks, while commercial water heaters see the highest demand around the middle of the day, although there is some variation depending on the type of commercial business. **TABLE 14** profiles a few GEB-relevant water heating technologies.

### *Appliances, Refrigeration, and Relevant MELs*

Appliances constitute a diverse group of end uses with various load shapes and operating behaviors, which necessitates different opportunities and challenges in providing grid services. Appliances that run in finite cycles, such as dishwashers and clothes dryers, have traditionally been considered candidates for DR programs because of the relative ease with which their operations can be modulated to run on lower power or temperature with minimal customer impact. Appliances that run continuously, such as refrigerators, require more careful planning to ensure that their main consumer function is maintained. Those appliances are more likely to benefit from modulating their consumption or, in the case of refrigerators, load shifting by careful precooling strategies to prevent damage to the contents. **TABLE 15** profiles a selection of GEB-relevant appliance and MELs technologies.

### *Natural Gas Technologies*

Natural gas technologies can also provide grid (both natural gas and electric) flexibility. This Technical Report considers three primary categories of natural gas technologies based on their grid value: combined heat and power (CHP), gas-fired variants of electric technologies and appliances, and dual-fuel systems or appliances. **TABLE 16** profiles building-scale CHP, while the others are covered in earlier tables.

### *Cross-Cutting Technologies*

**TABLE 17** profiles a selection of cross-cutting technologies that can provide demand flexibility across more than one of the end-use areas covered by this Technical Report, including HVAC, water heating, appliances, and refrigeration.

## Technical Challenges and R&D Opportunities

In order to unlock the full demand flexibility potential of the identified technologies in **TABLES 18-22**, certain technology-specific challenges need to be addressed. These can be addressed through identified R&D opportunities. **TABLES 18-A AND 18-B** summarize the technical challenges and the R&D opportunities discussed in the Technical Report on HVAC, Water Heaters, Appliances, Refrigeration, and MELs.

## Lighting and Electronics Technical Report Summary

This Technical Report focuses on lighting technologies and electronics that have the potential to provide grid services and helps identify R&D opportunities to improve their ability to provide grid services across varying time-scales (e.g., continuously to a few days per year). All lighting technologies are assumed to be light-emitting diodes (LED) or organic light-emitting diodes (OLED). The report discusses existing and new residential and commercial building lighting technologies. Among electronics, the report covers electric componentry (circuitry, optics, wires, etc.), internal controls, sensors, software, and algorithms, networked controls, retrofit controls, and other components. The ability to deliver grid value hinges on the necessary communications infrastructure to connect utilities directly to the end-use loads or to the technologies/building energy control systems. In many circumstances, energy efficiency is the greatest grid benefit that lighting and consumer electronics/IT equipment can provide.

### *Lighting*

Many new commercial building lighting control systems can receive and respond to grid signals, yet the market penetration of this technology is low. The report noted that in 2017, a study of OpenADR-compliant products found that only 6 out of 128 were lighting control systems. A 2018 survey of 155 U.S. utilities found that only 8 utilities reported having commercial and industrial customers leveraging automated lighting controls for DR (compared to 23 utilities for HVAC). **TABLE 19** summarizes a selection of GEB-relevant lighting technologies

### *Electronics*

In addition to lighting, the rapid growth of consumer electronics, data centers, and related information technology (IT) equipment makes electronics an increasingly viable candidate to provide grid services. Consumer electronics and IT equipment are typically not manufactured or used to provide demand flexibility; however, direct load control can be enabled through smart plugs, connected smart

| End-Use | Technology | Challenges | R&D Opportunities |
|---|---|---|---|
| **HVAC** | All HVAC GEB Technologies | Limited understanding of duration, temperature, and humidity constraints for curtailment. GEB capabilities of HVAC will depend on the building envelope. | Model and test to characterize curtailment limitations. Evaluate the role of envelope, insulation, infiltration, and solar gain, related to HVAC system efficiency and type. |
| | Separate Sensible and Latent Space Conditioning | Complex installation and commissioning | Develop packaged systems to reduce installation and commissioning complexity. |
| | Liquid Desiccant TES | Complex installation and commissioning | Develop packaged systems to reduce installation and commissioning complexity. |
| | | Generally high floorspace needs | Develop novel TES materials with increased energy storage density (volumetric and gravimetric) and packaging. |
| | Advanced Controls for HVAC Equipment with Embedded Thermostats | Lack of non-premium products with grid-interactive functionality | Develop inexpensive retrofit grid-interactive packages. |
| **Water Heaters** | Water Heaters with Smart, Connected Controls | Lower heat-pump-only preheat capabilities from HPWH vs. electric resistance | Evaluate the optimal approach for hybrid electric resistance/ HPWHs for curtailment.<br>Develop low-GWP refrigerant-based (e.g., carbon dioxide) HPWHs for higher-temperature capabilities. |
| **Appliances, Refrigeration, and Relevant MELs** | Modulating, Advanced Clothes Dryers, Advanced Dish and Clothes Washer Controls, Connected Refrigerator/ Freezer Advanced Controls, Water Heating | Lack of non-premium products with grid-interactive functionality | Develop inexpensive retrofit grid-interactive packages. |
| | Modulating, Advanced Clothes Dryers | High product cost (heat pump models) | Conduct cost-reduction R&D for heat pump clothes dryers. |
| | Advanced Controls for Commercial Refrigeration | Lack of broad understanding of duration and temperature constraints for curtailment | Model and test to characterize curtailment limitations. |
| | Modulating, Advanced Clothes Dryers | Lack of non-premium products with grid-interactive functionality | Develop inexpensive retrofit grid-interactive packages. |

**TABLE 18-A: TECHNICAL CHALLENGES AND R&D OPPORTUNITIES FOR HVAC, WATER HEATERS, APPLIANCES, REFRIGERATION, AND MELS**

| End-Use | Technology | Challenges | R&D Opportunities |
|---|---|---|---|
| **Natural Gas** | Building-Scale CHP | High product and installed costs | Conduct cost-reduction R&D with a focus on smaller- scale (e.g., <50 kilowatt [kW]) systems. |
| **Cross-Cutting Technologies** | Thermal Energy Storage | Complex installation and commissioning | Develop packaged systems to reduce installation and commissioning complexity. |
| | | Large space requirements/footprint | Develop novel TES materials with increased energy storage density and package storage systems. |
| | | Limited flexibility of thermal storage materials for year-round use | Develop novel ways to modify TES materials to dynamically manipulate their transition temperature. |
| | | | Determine the conditions for thermal storage operation that offer the greatest GEB service provision potential and energy savings potential. |
| | Modulating- Capacity Vapor Compression | High product costs | Develop lower-cost modulating-capacity systems, with a focus on heat exchangers and compressors. |
| | NVC Materials/Systems | High product costs | Develop lower-cost NVC materials, systems, and components. |
| | | Nascent solutions have limited field validation of architectures and approaches | Expand development of NVC for a broad range of HVAC and refrigeration applications. |

**TABLE 18-B: TECHNICAL CHALLENGES AND R&D OPPORTUNITIES FOR HVAC, WATER HEATERS, APPLIANCES, REFRIGERATION, AND MELS**

strips, load control switches, and home hubs. The primary market for grid-interactive consumer electronics and IT equipment is large commercial office buildings and data centers. As the energy efficiency of core loads has improved, the proliferation and energy consumption of MELs have increased. **TABLE 20** summarizes a selection of GEB-relevant electronics technologies.

## Technical Challenges and R&D Opportunities

**TABLE 21** summarizes the challenges and the R&D opportunities for Lighting and Electronics as identified in the Technical Report.

## Windows and Opaque Envelope Technical Report Summary

Building envelope technologies such as windows and opaque envelop solutions can reduce both summer and winter peak electricity demand. A building envelope can reduce peak demand by effectively managing heat transfer between conditioned spaces or between conditioned and unconditioned spaces through high thermal resistance, minimal thermal bridging, and effective air sealing. This peak-period demand reduction capability does not require dynamic or time-varying operation and is an inherent feature of a high-performance building envelope. However, there

| Technology | Definition | DF Potential |
|---|---|---|
| **Advanced Sensors and Controls** | Advanced sensors and controls enhance connected lighting systems with an improved ability to use algorithms to automatically modulate lighting levels or potentially other power-consuming features (e.g., spectrum, reduced sensor, or network communication interface power) in response to external grid/pricing signals. | High |
| **Hybrid Daylight Solid-State Lighting (SSL) Systems** | Hybrid daylight SSL systems are connected lighting systems that collect and redistribute natural daylight. Daylighting technologies include window and skylights as well as daylight concentrating systems, including solar collectors (often a mirrored lens with a sun tracker), beam splitters to filter out nonvisible light, and a light guiding and diffusing system to distribute the daylight in the building (e.g., fiber-optic cables, light pipes, mirrors). | Medium |
| **SSL Displays** | SSL displays are a system of connected lighting displays leveraging either LED or OLED technology to eliminate the need for windows and skylights as sources of daylighting. This technology consists of energy-efficient SSL displays in a networked system that mimic the daylighting and sun exposure that occupants would experience through a building's window or skylight. | Low |

**TABLE 19: STATE-OF-THE-ART GEB LIGHTING TECHNOLOGIES**

| Technology | Definition | DF Potential |
|---|---|---|
| **Continuous Operation Electronics** | Examples include desktop computers, servers, network equipment used for computing, data storage, and network supply. | High |
| **Battery-Powered Electronics** | Examples include laptop computers, smartphones, e-readers, tablets, and UPS battery backups. Controls can be built into the device itself. | Medium |
| **Electronic Displays** | Examples include integrated OLEDs and LEDs. | Low |

**TABLE 20: STATE-OF-THE-ART GEB ELECTRONICS TECHNOLOGIES**

are technologies–both emerging and commercialized–that can dynamically modify their properties to improve envelope performance under varying interior and ambient conditions. Dynamic operation of the envelope could be triggered in response to immediate or forecasted need for reserve capacity, changes in renewable generation output, or direct changes in electricity demand.

### Windows

State-of-the-art windows are characterized by a low U-factor (i.e., lower heat transfer between the building interior and exterior ambient conditions) and a suitable solar heat gain coefficient for a given climate zone and orientation. U-factors are affected by both the window frame and glazing materials, design, and construction, though recent developments in glazing technology appear poised to deliver larger near-term

| End-Use | Technology | Challenges | R&D Opportunities |
|---|---|---|---|
| **Lighting** | Advanced Sensors and Controls | Load shedding can be used for automated demand response (ADR) and/or building peak demand-side management, but requires grid-responsive communication<br><br>Uniform, standards-based DR signals that provide a consistent sequence of operations are yet to be specified<br><br>Appropriate dimming "depth" has not been agreed upon | Research should answer the appropriateness of various lighting curtailment protocols and the signaling and sequence of operations that regulators use to communicate how advanced lighting controls respond.<br><br>Research is needed on methods for embedding sensors directly in lights to enable multiple methods of control and to improve signal-processing, reduce error, and increase task-specific abilities. |
| | Hybrid Daylight SSL Systems | Maintenance and installation difficulties are major challenges<br><br>Lack of prototypes that demonstrate feasibility and value to the grid | More complex technology integration is needed, including photosensors and automated dimming controls that can adjust lighting based on daylight availability.<br><br>Prototype hybrid daylight system products are needed that are designed to respond to grid signals autonomously.<br><br>DR protocols need to be developed. |
| **Electronics** | All Electronics | Electronics capable of communicating and adapting seamlessly in a multivendor environment are lacking<br><br>Protocols and architecture to allow electronics to receive and respond to grid/pricing signals are needed<br><br>The control intelligence, particularly with the long-term vision of autonomous control, is lacking<br><br>Mechanisms to assure user trust in the communications and control algorithms to behave justifiably and equitably are lacking | R&D is needed to develop commercially available grid-responsive technologies accounting for highly variable energy use patterns. |

**TABLE 21: TECHNICAL CHALLENGES AND R&D OPPORTUNITIES FOR LIGHTING AND ELECTRONICS**

| Technology | Definition | DF Potential |
|---|---|---|
| **Photovoltaic Glazing** | Photovoltaic glazing selectively absorbs a portion of the visible light wavelengths, allowing the remainder to pass through the glass. | Medium |
| **Automated Window Attachments** | Standard window attachments include interior devices (e.g., blinds, shades) and exterior devices (e.g., awnings and shutters). These attachments can be repositioned to control glare and perimeter zone heating, and provide privacy. Adding network connectivity, light sensors, and control software to automatically actuate attachments helps minimize HVAC and lighting energy use while maximizing occupant comfort. By reducing peak demand with improved control over solar heat gain and reduced lighting energy use during peak hours, they can help provide grid services. | High |
| **Dynamic Glazing** | Dynamic glazing includes a range of chromodynamic coatings that can switch between two or more states to block portions of the wavelengths, thereby reducing solar heat gain in buildings. | High |

**TABLE 22: STATE-OF-THE-ART GEB WINDOWS TECHNOLOGIES**

performance improvements compared to the current state-of-the-art. The value of further improvements in the glazing U-factor will be limited until frames are improved. Triple pane insulating glass units (IGUs), which add a suspended center lite to a double-pane IGU, significantly reduced U-factors for both new and retrofit windows. In the future, design, durability, and performance improvements in vacuum-insulated glazing (VIG) might also lead to more mainstream availability and adoption. **TABLE 22** summarizes the relevant windows technologies from the Technical Reports.

## Opaque Envelope

Static state-of-the-art opaque envelope technologies offer a high R-value (i.e., higher resistance to heat transfer between the building interior and exterior ambient conditions) per inch of insulation material. The best materials include vacuum-insulated panels (VIPs) and fiber-reinforced aerogels, though these have seen limited application in buildings because of high costs, durability, and product availability challenges.

In addition to static opaque envelope technologies, there are both prospective and currently commercialized materials and technologies that can dynamically modify their properties to improve envelope performance under varying interior and ambient conditions. Dynamic operation of the envelope could be triggered in response to immediate or forecast need for reserve capacity, changes in renewable generation output, or actual reductions or increases in electricity demand. A response to these grid service requests that is coordinated between the dynamic envelope components and both the HVAC and lighting systems is likely to yield the largest potential response and the greatest control over the response from any individual building.

In some climate zones, it is conceivable that a building envelope with a wide dynamic range and active thermal storage control could operate without an HVAC system, thus eliminating the coordinated HVAC and envelope control benefits, though this will require the development and commercialization of multiple active envelope technologies. **TABLE 23-A AND 23-B** summarize the relevant envelope technologies from the Technical Reports.

| Technology | Definition | DF Potential |
|---|---|---|
| **Building-Integrated Photovoltaics** | Smart thermostats sense the temperature conditions inside a building and control the attached HVAC equipment to maintain the target conditions to maintain thermal comfort. | High |
| **(BIPV)** | BIPV supplements exterior building facade materials with materials that incorporate PV cells for power generation. BIPV is distinct from PV glazing in that BIPV applies to the opaque portion of the envelope–exterior cladding or sheathing and roofing materials. BIPV is also distinct from traditional off-the-shelf PV panels mounted to the roof or facade using a racking system. BIPV is designed to integrate into the aesthetic of the building, generally finished flush with the surrounding roof or facade, and sometimes mimicking the appearance of roof shingles, cladding panels, or siding. | Low |
| **Variable Radiative Technologies** | Cool roofs and other cool building surfaces are well-established products that can deliver proven cooling energy savings, have good long-term durability, and are cost-effective. However, they are passive solutions. Materials that can operate more like dynamic glazing (particularly electrochromic) could facilitate demand flexibility by reducing both peak heating and cooling loads. | Medium |
| **Moisture Extraction and Storage** | Moisture control is a significant contributor to cooling energy use in buildings, and cooling energy is a major driver of peak electricity demand. Envelope components–particularly those with surfaces exposed to indoor air that can not only store water temporarily, but actively extract moisture on demand from the indoor environment and use adjacent systems to reject it to the surroundings – would complement existing moisture storage and reduce cooling energy use. | Medium |
| **Thermal Storage Materials** | Thermal storage materials store heat or cool when charged by conventional HVAC systems and release heat passively when discharging. These materials can thus reduce and shift the timing of heating or cooling energy demand. | High |
| **Thermally Anisotropic Materials (TAS)** | TAS describe materials with engineered layer(s) with alternating high and low thermal conductivities. The high conductivity layer(s) must be connected to a heat sink or source. TAS have anisotropic thermal transport properties, because the high conductivity layer(s) are the least resistive paths for heat transfer, thus helping reroute heat flow through the envelope to the connected heat sink or source. TAS also might have the potential to be dynamically controlled by changing the heat transfer characteristics of the connection between the TAS and the heat sink or source. | High |

**TABLE 23-A: STATE-OF-THE-ART GEB ENVELOPE TECHNOLOGIES**

| Technology | Definition | DF Potential |
|---|---|---|
| **Tunable Thermal Conductivity Materials** | Tunable thermal conductivity materials can dynamically adjust their thermophysical properties. As an example, in the cooling season, a tunable thermal material would have high thermal conductivity (low R-value) when ambient temperatures are lower than the indoor temperature, thereby providing cooling without the HVAC system. Similarly, this material would have low thermal conductivity (high R-value) when relative indoor and outdoor temperatures are reversed, minimizing thermal losses to the exterior and ensure no build-up of latent loads. | High |
| **HVAC and Hot Water Combo Systems** | Combination space/water heaters efficiently heat water and provide space heating. There are three basic configurations: 1) Indirect space heating: systems that heat water for domestic use and circulate hot water through a finned-tube coil, which transfers heat to air that is blown over the coil, 2) Indirect water heating: systems that heat water for space heating and either utilize a heat exchanger in the boiler to heat domestic water or redirect the flow of heated water through the domestic hot water storage tank as necessary, 3) Integrated heat pump systems that provide space heating, space cooling, and domestic hot water together or independently. | High |

**TABLE 23-B: STATE-OF-THE-ART GEB ENVELOPE TECHNOLOGIES**

### Technical Challenges and R&D Opportunities

**TABLE 24-A, B, AND C** summarizes the challenges and the R&D opportunities for Windows and Envelope as identified in the Technical Report.

## Whole-Building Controls, Sensors, Modeling, and Analytics Technical Report Summary

The technologies in Chapter 3, **TABLE 1**, and Section 1 of this appendix, cover the hardware, appliances, equipment, and packaged materials associated with the building structure. To activate the GEB potential of these physical systems, they need to be layered with sensors, controls, and communication technologies. Local controls interact with single devices such as a smart thermostat controlling an air conditioner. Supervisory controls interact with multiple end-uses or distributed energy resources. **TABLE 25** defines supervisory control technologies.

The capabilities of sensors, controls, and communications required for GEB can be classified into four key categories:

1. **Monitoring** the needs of and interaction with occupants, operators, and owners
2. **Execution** of controls to communicate and actuate the integrated systems to provide grid service delivery
3. **Prediction** of availability of flexible loads over a given time (e.g., 24 hours), and measurement and verification (M&V) of service delivery
4. **Quantitative** analysis for optimizing equipment operation, scenario analysis.

**TABLE 26** summarizes the specific R&D opportunities for sensors and controls.

In addition to the R&D opportunities for further developing the required capabilities for sensors and controls, there are two other key considerations for implementing these technologies in GEBs. Specifically, they are demand aggregation and interoperability, described below.

### Demand Aggregation

The extent to which various demand flexibility modes are aggregated within a building is an important design decision for a GEB. Demand flexibility modes also provide for an individual grid service and across multiple types of grid services (i.e., efficiency, load shed, load shift, and

| End-Use | Technology | Challenges | R&D Opportunities |
|---|---|---|---|
| **Windows and Envelope** | All Technologies | Grid Service-Specific Control Strategies That Can Balance Occupant Needs and Grid Benefits | Determine quantitative measures for occupant comfort.<br><br>Identify appropriate approaches for in-situ, real-time measurement of occupant comfort.<br><br>Develop acceptable out-of-the-box defaults for controls that balance demand flexibility, building owner costs (if any), and occupant comfort.<br><br>Develop adaptive control systems that achieve improved multi-objective outcomes (e.g., comfort, cost, productivity, grid services) and minimize user overrides.<br><br>Characterize conditions that lead to occupant overrides and develop strategies to minimize the probability of overrides. |
| | | Parameterization of Grid Response Capability | For technologies under development, employ preliminary multi-physics simulations of each GEB-relevant technology to explore the key figures of merit that influence demand flexibility.<br><br>Quantify the influence of identified figures of merit on time to initial response, response (ramp) rate, total capacity, and other characteristics relevant to providing the grid services.<br><br>Determine the appropriate value or range of values for each of the key parameters identified for a given technology to provide the various grid services that can be provided by that technology.<br><br>Develop deterministic quantitative methods for the design of sensors and control systems specific to each GEB-relevant technology. |
| | | Methods to Quantify Building-Specific Response Characteristics | Multiphysics simulation of the time-series interaction between GEB-relevant technologies and a range of residential and commercial buildings.<br><br>Easy-to-use design guidance for architects and engineers to specify and position sensors and control hardware so that relevant GEB technologies can deliver the expected grid services. |

**TABLE 24-A: TECHNICAL CHALLENGES AND R&D OPPORTUNITIES FOR WINDOWS AND ENVELOPE**

| End-Use | Technology | Challenges | R&D Opportunities |
|---|---|---|---|
| **Windows** | Dynamic Glazing and Automated Attachments | Off-the-shelf controls with GEB functionality<br><br>Complexity of sensor system configuration and commissioning | Novel building controls strategies that incorporate dynamic glazing and automated attachment functionality into their core capabilities, alongside HVAC systems and other building components.<br><br>Develop software tools for simple, low-effort sensor configuration planning and to verify installation and rapidly diagnose in-field faults.<br><br>Determine whether GEB operation introduces additional commissioning or sensor system requirements and adapt tools accordingly. |
| **Envelope Technologies** | Tunable Thermal Conductivity Materials | Breadth of potential operations and the relative demand flexibility potential of various materials and configurations<br><br>System physical and thermal response times<br><br>Effect of assembly on operational performance | Identify placement or applications, types of tunable thermal conductivity materials, or "circuit elements" that maximize demand flexibility.<br><br>Investigate the energy savings, cost benefits, and demand flexibility potential of coupled systems (i.e., tunable thermal conductivity materials designed for use as a package with other dynamic envelope technologies).<br><br>Quantify the value of increasing the response speed of tunable thermal conductivity materials.<br><br>Investigate the potential for more extensive changes in the envelope assembly to improve demand flexibility and energy savings.<br><br>Design novel assemblies that use tunable thermal conductivity materials to enhance the performance of other dynamic and tunable components for demand flexibility and overall energy savings. |
| | Thermally Anisotropic Materials | Components or technologies that enable switching (on/off) of connection to sink/source, enable rate control with connection to source/sink, and/or facilitate effective access to potential sources and sinks<br><br>Effect of assembly on operational performance | Develop novel materials or system designs that can effectively access thermal sinks and sources with minimal installation effort.<br><br>Develop thermal switch materials or mechanical devices that can control the connection between the anisotropic material and a related source/sink.<br><br>Investigate the potential for novel assemblies to improve performance, including coupling with other technologies.<br><br>Determine ideal envelope assembly characteristics to maximize GEB capability.<br><br>Design novel envelope assemblies that have improved compatibility with thermally anisotropic materials and composites. |

**TABLE 24-B: TECHNICAL CHALLENGES AND R&D OPPORTUNITIES FOR WINDOWS AND ENVELOPE**

| End-Use | Technology | Challenges | R&D Opportunities |
|---|---|---|---|
| | Tunable Thermal Conductivity Materials | Breadth of potential operations and the relative demand flexibility potential of various materials and configurations<br><br>System physical and thermal response times<br><br>Effect of assembly on operational performance | Identify placement or applications, types of tunable thermal conductivity materials, or "circuit elements" that maximize demand flexibility.<br><br>Investigate the energy savings, cost benefits, and demand flexibility potential of coupled systems (i.e., tunable thermal conductivity materials designed for use as a package with other dynamic envelope technologies).<br><br>Quantify the value of increasing the response speed of tunable thermal conductivity materials.<br><br>Investigate the potential for more extensive changes in the envelope assembly to improve demand flexibility and energy savings.<br><br>Design novel assemblies that use tunable thermal conductivity materials to enhance the performance of other dynamic and tunable components for demand flexibility and overall energy savings. |
| | Variable Radiative Technologies | Active control of operation<br><br>Fouling, condensation effects on performance | Develop materials that can alter key performance parameters in response to a control signal.<br><br>Develop thermal switch materials for heat conduction control with daytime radiative coolers. |

**TABLE 24-C: TECHNICAL CHALLENGES AND R&D OPPORTUNITIES FOR WINDOWS AND ENVELOPE**

load modulation). At one end, individual devices could interact with any entity outside the building directly (e.g., the electric grid, energy market, or service aggregator). At the other end, multiple devices could be coordinated by a supervisory controller and interact with the building as a unit. Furthermore, co-located buildings could coordinate with one another and package services at the district, neighborhood, or campus level. The building is likely a natural unit for grid services given that it is the unit of aggregation for many other services, both energy-related (e.g., grid connection, metering, billing) and otherwise (e.g., design, construction, purchasing, leasing).

Demand flexibility modes are largely independent of one another, and different modes can be aggregated at different

| Technology | Definition | DF Potential |
|---|---|---|
| **DF-Enabled BAS** | Automated DR and demand flexibility communication systems can be added to existing BAS using gateways and programming demand flexibility sequences in response to automated DR signals. This technology can also be native to the BAS in some cases without the addition of a gateway device. | High |
| **Smart Home Automation Systems (SHEMS)** | A SHEMS is a control and communication system designed to optimize energy use across multiple end-uses or DERs with energy-saving or grid services potential. | High |
| **Model Predictive Control (MPC)** | MPC allows building energy management systems to model multiple factors such as energy use, energy costs, grid services, economic incentives, occupancy, weather, and building services and determine optimal controls set points and equipment schedules. | High |
| **Multi-Building Control** | Multi-building control is the capability to communicate and control multiple buildings from a single aggregator platform, a connected community, or a district energy system. | High |

**TABLE 25: STATE-OF-THE-ART SUPERVISORY SENSORS AND CONTROLS TECHNOLOGIES FOR GEBS**

| Categories | R&D Opportunities |
|---|---|
| **Needs of Occupants, Operators, and Owners** | • Mechanisms for accurate, low-cost, non-intrusive, and privacy-preserving methods of measuring occupant comfort and occupancy schedules.<br>• Mechanisms to allow occupants to register their priorities for thermal comfort, lighting, and need for electronics and information technology.<br>• Mechanisms to collect information on whole-building state, committed grid services, potential compensation and financial incentives, expected risk to not deliver the commitment, potential occupant impact, and impact on equipment lifetime. |
| **Integrated Service Delivery** | Development, training, and calibration of a cost-effective model to predict control methods that are sufficiently accurate and robust. |
| **Characterization and M&V** | Consensus baseline algorithms that are continuously calibrated, resilient to statistical uncertainty, and can be composed to support characterization and M&V of multiple services. |
| **Quantitative Analysis** | Bridging the disconnect between traditional building energy management and control workflows. |

**TABLE 26: SENSORS AND CONTROLS R&D OPPORTUNITIES**

levels within a building. We consider the relative merits and drawbacks of aggregation by several criteria:

- **Overall system performance:** The most compelling advantage of aggregation within the building is overall system performance. By considering multiple options and evaluating their impacts on energy efficiency, the grid, and occupants, a GEB may be able to identify combinations of strategies that provide better performance and value than when individual strategies are considered and activated in an uncoordinated manner. This holistic approach is one of the premises (and promises) of GEBs and has been proven in the field (e.g., see Kjaergaard, et al., 2016; Hviid and Kjorgaard, 2018). At a minimum, devices that are part of the same end-use (e.g., fans and compressors in an HVAC system) should be coordinated. The ability to consider the overall system performance also reduces uncertainty. If a particular load reduction pathway is no longer available, an alternative can quickly be secured. This is even more relevant when aggregating across buildings.
- **Implementation complexity:** Integrating multiple disparate systems presents complexity and cost barriers that may go beyond additional hardware and software. The barriers often include project-specific technical barriers, such as incompatibility or lack of interoperability, either in communication protocols or control algorithm design. Barriers may also include nontechnical barriers, such as lack of staff bandwidth and expertise as well as poor fit with certain operational contracts.
- **Latency:** Building-level aggregation may impose additional latency on communication. This additional latency may be prohibitive fast modulation services.
- **Scalability:** In the case of grid services, scalability typically refers to the relationship of the number of steps in the market clearing algorithm or the number and size of messages sent as they relate to the number of individual providers of the service. Grid operators, service markets, and aggregators want to deal with as few individual actors as possible. Scalability is often managed using hierarchy, with the aggregation of different types taking place at different scales.
- **Security:** The objectives for enhanced security are to reduce vulnerabilities in individual devices to sabotage and the likelihood that a vulnerability in one device can spread to and compromise other devices – and eventually throughout the entire system. Building-level aggregation reduces individual device vulnerability by hiding devices behind a single gateway that can be secured. Device-level aggregation could reduce the likelihood that vulnerability in one device may compromise other devices, because it does not require devices to interact with other devices in the building. Device-level aggregation has an additional built-in benefit in that it allows the manufacturer to remotely update and patch devices in the field (Fairley 2015). Experts have also considered the opposite problem. A security breach on a single gateway could compromise all of the devices the gateway interacts with. There are two schools of thought on this complex topic where more research is needed.
- **Multi-building coordination:** With the exception of large commercial or industrial buildings, individual buildings do not typically provide grid services. Instead, services are provided by groups of buildings. Multi-building coordination can potentially improve grid services while minimizing impacts on individual buildings and their occupants. Multi-building coordination may be easier to implement than coordinating different end uses (or zones) within a single building because separate buildings do not physically interact with one another, nor do the preferences of their occupants. Only the cumulative effects of the resulting load shapes matter for grid services provision. However, multi-building coordination can encompass a much larger number of individual actors (e.g., hundreds of buildings in some cases) with limited capability to share information, especially bidirectionally. Some level of information sharing and coordination, even implicitly, is important to mitigate coincident effects if many buildings execute the same control strategies.

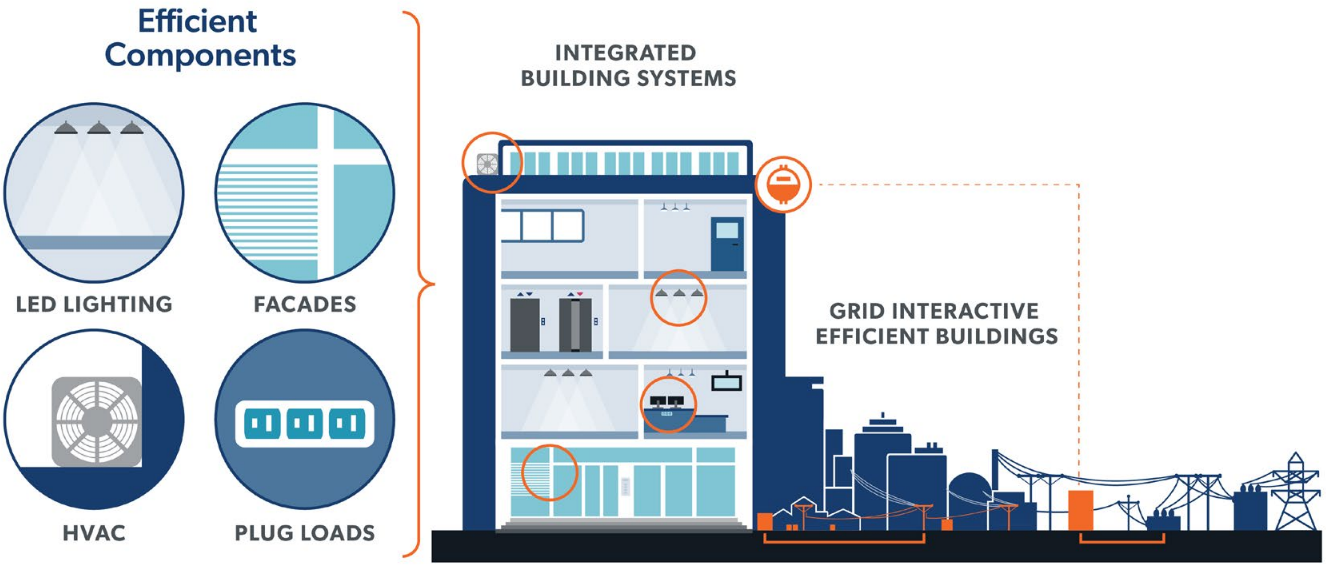



**FIGURE 36: EFFICIENT COMPONENTS, INTEGRATED SYSTEMS, AND COMMUNICATION WITH THE ELECTRIC GRID**

Manufacturers of building equipment and appliances (e.g., HVAC, water heaters) have emerged as likely aggregators for grid services. By communicating with similar devices as a fleet and selectively and remotely controlling subsets of those fleets, manufacturers can provide coordinated grid services, sometimes with substantial aggregated capacity (e.g., MW of demand flexibility).

## Interoperability

In addition to the layers described in Chapter 3, **FIGURE 8**, GEBs rely heavily on electronic communication within the building and between the building and the grid. Two important characteristics of electronic communication are interoperability (i.e., the ability of devices or software systems to reliably exchange information) and cybersecurity (i.e., the ability of devices and software systems to maintain availability, integrity, and privacy in the face of adversaries). The design of electronic communication is similar to Chapter 3, **FIGURE 8**, with different protocols operating at different layers. One important gap is the need for standard semantic data models of buildings, their systems, and their capabilities. Semantic data models allow new devices and services to automatically configure to different buildings, similar to the "plug-and-play" feature common in the consumer electronics industry.

**FIGURE 36** illustrates two layers where interoperability is needed: **1)** within a building to create integrated systems and **2)** from the building to the grid for the building to be interactive. There are a number of efforts to improve interoperability within the building. For example, BACnet is a common protocol for interoperable commercial building control systems. Emerging standards for data interoperability also include Haystack, the Brick schema, ASHRAE Standard 223.[82] Standards to support Interoperability between the building and the grid include CTA-2045, OpenADR, and IEEE 2030.5 Smart Energy Profile. CTA-2045 has both a hardware and a software interface. OpenADR is software only and can be deployed using various physical forms. Similarly, IEEE 2030.5 is a software specification that can use TCP/IP or other physical layer radios such as IEEE 802.11 for lower-

82 https://project-haystack.org, https://brickschema.org/, and ASHRAE Standard 223P, Designation and Classification of Semantic Tags for Building Data.

| Name | Organization |
| --- | --- |
| Antonio Bouza | DOE |
| P. Marc LaFrance | DOE |
| Sven Mumme | DOE |
| Erika Gupta | DOE |
| Amir Roth | DOE |
| Brian Walker | DOE |
| Wyatt Merrill | DOE |
| Ayyoub Momen | ORNL |
| Kyle Gluesenkamp | ORNL |
| Diana Hun | ORNL |
| Michael Starke | ORNL |
| Janet Reyna | NREL |
| Kim Trenbath | NREL |
| Chioke Harris | NREL |
| Draguna Vrabie | PNNL |
| Michael Poplawski | PNNL |
| Luís Fernandes | LBNL |
| Christian Kohler | LBNL |
| Marco Pritoni | LBNL |
| Jared Langevin | LBNL |

**TABLE 27:** TECHNOLOGY EXPERTS

layer protocols. CTA-2045, OpenADR, and IEEE 2030.5 are all application-layer protocols but may have some lower-layer capabilities – as mentioned in reference to the IEEE 802.11.[83]

## Expert Workshops Summary

We collaborated with technology experts from across DOE National Laboratories and BTO staff to contribute to key aspects of the GEB *Roadmap* through a series of three online working sessions from June to July, 2020. The technology expertise represented by the invitees included HVAC, appliances, building envelope and windows, plug load and electronics, sensors & controls, data analytics & modeling (see **TABLE 27**).

The first workshop was focused on reviewing the Technical Reports towards an overall GEB vision and roadmap. Specifically, participants were asked to identify additional challenges to GEB adoption; and provide feedback for draft summaries of the Technical Reports to be included in the

83 V. M. Tayur and R. Suchithra, "Review of interoperability approaches in application layer of Internet of Things," *2017 International Conference on Innovative Mechanisms for Industry Applications (ICIMIA)*, Bangalore, 2017, pp. 322-326, doi: 10.1109/ICIMIA.2017.7975628.

| Technology | GEB layer | Market Status |
|---|---|---|
| Automated Attachments | Physical Systems | Commercially available |
| Smart Thermostats | Local control | Commercially available |
| Heat Pump Water Heaters | Physical Systems | Commercially available |
| District Energy TES | TES | Commercially available |
| TES in HVAC | TES | Pilots & limited availability* |
| Dynamic Glazing | Physical Systems | Pilots & limited availability |
| DF-Enabled Water Heaters | Local Control | Pilots & limited availability |
| Heat Pumps | Physical Systems | Pilots & limited availability |
| DF-Enabled Appliances and MELs | Physical Systems | Pilots & limited availability |
| DF-Enabled BAS | Supervisory Control | Pilots & limited availability |
| DF-Enabled SHEMS | Supervisory Control | Pilots & limited availability |
| DF-Enabled Connected Lighting | Local control | Pilots & limited availability |
| TES in Refrigeration | TES | Pilots & limited availability |
| DF-Enabled Predictive Control | Supervisory Control | Pilots & limited availability |
| HVAC and Hot Water Combo Systems | Physical Systems | Pilots & limited availability |
| DF-Enabled Multi-Building Control | Supervisory Control | Pilots & limited availability |
| TES in Building Envelope | TES | In development |
| New TES Materials | TES | In development |

**TABLE 28: SUMMARY OF IMPORTANT GEB TECHNOLOGIES**

***TES integrated with HVAC is common in large commercial buildings but rare in small commercial or residential buildings.**

*Roadmap.* Participants were also asked to prioritize GEB technologies based on qualitative criteria such as demand flexibility, cost, usability, system readiness, and developed technology sets or "bundles" that could be integrated to further enhance demand flexibility in buildings

The second workshop delved further into GEB technology bundles. Participants began by drafting a cohesive framework for integrated GEB technologies. Dubbed "GEB layers," the framework described features and attributes of GEB comprising of hardware and equipment, sensing, local control, supervisory control, and building to grid interface as layers on top of each other for each building service type (e.g., thermal comfort, hot water, refrigeration). Additional distributed energy resources would also be integrated with the GEB layers, such as photovoltaics, electric vehicles, and battery storage. Participants also reviewed and refined technology bundles and discussed integration challenges associated with technology bundles according to different building types (e.g., residential; small, medium, and large commercial), existing building retrofits, and new construction. The participants prioritized technical barriers but not policy, regulatory and economic or financial barriers. The participants were also asked to identify the stakeholders that would be impacted by the challenges, as well as those stakeholders that would be needed to address the challenges identified.

The third workshop gathered participant input on the GEB vision for technology. The participants also considered specific visions for residential and commercial buildings. A refinement of the GEB layers was presented for additional feedback. Finally, participants sorted the barriers into categories (e.g., technological, policy, market design, pricing) and discussed opportunities or solutions for overcoming the barriers.

## Prioritization Survey for Technology Development Pipeline

In Chapter 3, **FIGURE 8**, we provided a description of GEB technology layers that first identified foundational building services. These building services are provided by physical end-use equipment, hardware, structures, the building envelope, and appliances. GEBs can benefit from improvements in these physical end-use and structural systems. Chapter 3, **FIGURE 9**, gives examples of important technologies necessary to achieve advanced GEB.

In the figure, those below the market status timeline are the physical systems such as HVAC equipment and building envelope. Technologies above the market status timeline – referred to as "DF-Enabled" – denote the additional capabilities of the technology to automatically respond to grid signals and provide grid services. These include local and supervisory control DF-enabling technologies. DF-enabling technologies such as Appliances and MELs, when combined, could provide new grid services. Thus, Appliances and MELs are listed in **FIGURE 9** as a DF-enabled group.

Numerous efforts are underway to provide grid-communication and control with these devices and systems. **TABLE 28** shows the market status of the selected technologies as represented in the technology pipeline figure (Chapter 3, **FIGURE 9**). The market status from "in development" to "pilots and limited availability" to "commercially available" is a continuum along the timeline; the placement is a general characterization of status.