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

Grid-interactive Efficient Buildings

Projects Summary

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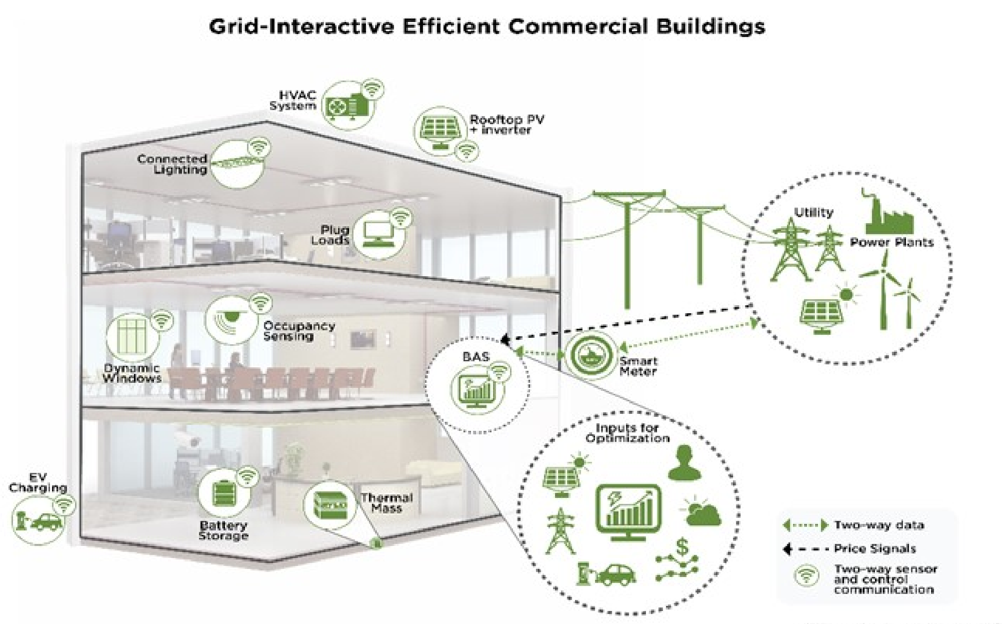
SUMMARY OF ACTIVE BTO GEB PROJECTS

Buildings offer a unique opportunity for cost-effective demand-side management, because they are the nation's primary users of electricity: 75% of all U.S. electricity is consumed within buildings, and perhaps more importantly, building energy use drives a comparable share of peak power demand. The electricity demand from buildings results from a variety of electrical loads that are operated to serve the needs of occupants. However, many of these loads are flexible to some degree; with proper communications and controls, loads can be managed to draw electricity at specific times and at different levels, while still meeting occupant productivity and comfort requirements. Through its grid-interactive efficient building (GEB) research, DOE's Building Technologies Office seeks to build on existing energy efficiency efforts to optimize the interplay among energy efficiency, demand response, behind-the-meter generation and energy storage to increase the flexibility of demand-side management. BTO envisions a future where buildings dynamically operate as part of a low-cost, reliable electricity grid while meeting the needs and expectations of building occupants.

BTO's mission supports the R&D, validation, and integration of affordable, energy efficiency technologies, techniques, tools, and services for U.S. buildings (existing and new, residential and commercial). In support of this mission, BTO is developing a GEB strategy that aims to optimize energy use across DERs to advance the role buildings can play in energy system operations and planning. This summary covers key projects contributing to the grid-interactive efficient buildings work and breaks projects into four areas of focus:

- Value Proposition for GEB
- Building Technologies for Flexible Loads
- Optimization of Buildings for Flexible Loads
- Validation & Verification of Building Performance for Grid Services



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This document focuses on active projects that build on the foundation of BTO's EE work (it does not include core EE work) and the R&D needed to enable building technologies to provide flexible building loads. It is difficult to precisely delineate what is a "GEB project" and there are GEB-relevant projects that are not included in this summary (at BTO and other offices).

Additional BTO GEB materials can be found here; including an Overview (44 pp.) and a Fact Sheet (1 p.).

1. Value Proposition for GEB

Includes analysis for national and sectoral GEB potential, research on inputs needed for determining the impact of flexibility on building load shapes and the electricity system, and work related to GEB stakeholder value propositions.

1.1 Valuation Inputs

In order to properly value flexibility temporal and locational considerations must be accurately captured.

1.1.1 End Use Load Shapes

(FY19-21; NREL/LBNL): This project will result in: 1) end-use load profiles for U.S. building stock at both aggregate and individual building scales; 2) calibrated building stock end use models with ability to estimate EE/DR savings profiles for existing and emerging technologies. These datasets and associated methodology will be made publicly available.

1.1.2 Time Sensitive Valuation

(FY20; LBNL): This project will advance the consideration of the value of energy efficiency during times of peak electricity demand and high electricity prices by summarizing analysis that quantifies the additional benefits of electric efficiency measures/programs during these periods. The project will cover two areas: 1) documenting existing studies that estimate the time-varying energy and demand impacts of efficiency measures/programs in multiple geographic regions and 2) summarizing end-use load research data available for this purpose and application of the data in electricity resource planning.

1.1.3 Locational Value of Distributed Energy Resources

(SPIA) (FY20; LBNL): This project, while not managed by BTO, is aligned with BTO's GEB priorities. It focuses on how different types of distributed energy resources (DERs) provide different value based on DER location and how the value of DERs change depending on the type of feeder to which they are interconnected and its characteristics. The project will produce a technical report considering these aspects, as well as approaches state regulators and policymakers use to estimate the benefits and costs of DER investment with respect to their locational value.

1.2 GEB Potential Analysis

Estimate the impact that energy efficiency and demand response measures (flexibility) will have on aggregate building load shapes and the electricity system.

1.2.1 GEB Technical Report Webinar Series

(FY20; BTO): BTO is holding a webinar series covering the recent publications on the grid-interactive efficient buildings technical reports. These reports provide researchers with an understanding of the flexibility opportunities of building loads for grid services. The webinar series will include six topics:

- Heating, Ventilation, & Air Conditioning (HVAC); Water Heating; and Appliances
- Lighting & Electronics
- Building Envelope & Windows
- Sensors & Controls and Modeling & Data Analytics
- Building Equipment Integration
- Distributed Energy Resources Integration

1.2.2 National GEB Roadmap

(FY20-21; LBNL/Brattle): This project will estimate the value of the untapped GEB opportunity, identify and prioritize barriers to achieving the GEB potential, and define key solutions for overcoming the barriers, including actionable next steps for DOE and all key industry stakeholders.

1.2.3 System-Level Assessment of EE&DR

(FY19-21; LBNL): This project will develop a new integrated valuation methodology based on energy efficiency (EE) and demand response (DR) measure load shapes and regional electricity features to assess the load and economic relationships of EE and DR. Key deliverables include: 1) a technical report summarizing a conceptual framework of criteria driving interactive EE/DR effects with a detailed analysis of the ways in which specific EE and DR measures (and portfolios thereof) interact with one another; 2) a database of typical, regionally representative end-use load shapes with the highest potential for interactive EE/DR effects; and 3) a quantification of changes in system-level costs from the addition of different EE and DR measure portfolios.

1.2.4 Understanding the Impact of Demand Response on Building Energy Efficiency Metrics

(FY19-21; SLAC): This project will analyze the impact DR capabilities have on the efficiency of buildings and the impact that EE strategies may have on demand response capacity. Results of this analysis will be presented in a technical report and incorporate data from three different locations in the analysis.

1.2.5 Framework and Methodology to Define Flexible Loads in Building

(FY19-21; LBNL): This project advances methods quantifying buildings' flexibility from a regional and building type perspective. The project will incorporate bottom-up techniques to create a consistent framework and methodology that defines buildings' grid resource flexibility. The research will determine a building's grid-resource flexibility based on factors including climate/weather, location, space types and operation history/status. Typical building end-uses such as: HVAC, lighting, miscellaneous electric loads (MELS), refrigeration and certain process loads, etc., will be considered as appropriate. The work will include validation testing in FLEXLAB and model results; project outputs will be shared in a technical report and will include publicly available metrics and calculation procedures.

1.2.6 Load Flexibility Study

(FY19-20: NREL): This project involves a high-level stochastic analysis of the main value streams (including capacity, energy, and ancillary services) for building flexibility, by leveraging NREL's Standard Scenarios and the prototype Cambium tool. The analysis will hinge on defining generic flexible resources to be analyzed. These flexible resources will represent potential GEBs that shift loads within a 24-hour window and will be chosen in collaboration with BTO and NREL's building experts.

1.3 Stakeholder Value Streams and Analytical Needs

Identify key stakeholder needs in order to value flexibility under current frameworks and determine future analytical resources.

1.3.1 Utility Working Group

(FY19-20; ACEEE): A webinar series that will result in a summary of best practice approaches and challenges/gaps related to utility programs supporting the integration of EE/DR programs or GEB pilots.

1.3.2 Regulators and State Energy Office Working Group

(FY19-20; NASEO/NARUC): A webinar series to learn about the needs and questions of state leaders related to the value proposition of flexibility. This project will result in a set of documents that will support the development of state flexibility roadmaps and the initiation of state-led pilot projects. The GMLC technical assistance project described below will support states participating in this working group.

1.3.3 Better Buildings Commercial Buildings-to-Grid Working Group

(FY19-20; NREL): This project will work with Better Buildings Alliance and Challenge partners to understand key opportunities and challenges in the commercial sector, as well as document the size of the building resource to the grid across a set of diverse building portfolios or geographies.

An important Grid Modernization Laboratory Consortium (GMLC) foundational project for FY20-21 that BTO is co-funding on behalf of EERE focuses on direct technical assistance (TA) over two years to state energy offices (SEOs) and public utility commissions (PUCs) to advance buildings that can provide grid services through demand flexibility—using distributed energy resources (DERs) to reduce, shed, shift, modulate and generate electricity. TA will support four key topics related to GEB and demand flexibility: programs and policies in public buildings, potential, pilots, and valuation. This work is in partnership with the NASEO-NARUC working group.

Another important collaborative effort BTO participates in is the SEE Action Network. This group has focused on developing a series of GEB related reports, two of which were published in FY20: 1) *An Introduction for State and Local Governments* and 2*) Determining Utility System Value of Demand Flexibility.* A third report that is forthcoming, *Issues and Considerations for Advancing Performance Assessments of Demand Flexibility*, will summarize current practices and opportunities to encourage robust and cost-effective assessments of demand flexibility performance and improve planning and implementation based on verified performance.

2. Building Technologies for Flexible Loads

Includes identification of building technologies and R&D opportunities that can provide greater building flexibility. The projects below do not include core EE work that is an important foundation to GEB but instead focus on exploring how to make building technologies more flexible.

2.1 Lighting

2.1.1 Characterization of Connected Lighting Systems Potential to Provide Grid Services

(FY19-21; PNNL): Connected lighting systems (CLS) incorporating solid-state lighting (SSL) technology have the potential to provide a broad range of electric grid services, including those that rely on fast response. SSL power draw can be quickly modulated by dimming deeply and varying light spectrum and distribution, and thereby provide grid services at time frames of hours (e.g., for energy services) to seconds or less (e.g., for frequency regulation). However, the ability of CLS to deliver potential grid services while simultaneously delivering sufficient lighting service and occupant satisfaction has not yet been proven or quantified. This project will evaluate and advance the ability of CLS to provide grid services through modeling and simulation, laboratory testing, and field testing. Project results will be disseminated via targeted mechanisms to technology developers, lighting manufacturers, building owners and operators, system integrators, industry standards organizations, and other researchers. This project aims to advance the use of CLS towards achieving the 8 GW national peak reduction potential that has been estimated for grid-integrated lighting by 2035.

2.1.2 Connected Lighting Systems

(FY19-21; PNNL): The objective of PNNL's connected lighting systems research is to increase the likelihood that emerging products and integrated systems will result in significant lighting (as well as non-lighting) energy savings, lighting service improvements, and value-added benefits for building owners and occupants, as well as city managers and residents. This task area defines technical research in six areas that are key to enabling the energy savings potential of CLS: energy reporting accuracy, system-level energy performance, interoperability and system integration, key new features, cybersecurity vulnerability, and grid integration. The majority of the proposed work is carried out in the Connected Lighting Test Bed (CLTB) established by PNNL in Portland, OR, and focuses on examining and revealing common challenges and limitations as well as potential value-added opportunities emerging from CLS technologies.

2.2 Building Envelope and Windows

2.2.1 Solid State Tunable Thermal Energy Storage for Smart Building Envelopes

(FY19-21; LBNL/NREL): This project will develop phase change materials (PCMs) that undergo solid-solid phase change and allows for dynamic tunability of the transition temperature. This research will enable a next generation of grid-interactive building thermal management schemes, capable of micro-zoned thermal energy control, spatial and temporal control of thermal energy storage, and dynamic control of heat flow throughout the building.

2.2.2 Thermal Switch Materials for Building Envelopes: A New Paradigm for Spatial and Temporal Optimization of Building Thermal Energy

(FY19-21; LBNL/NREL/SLAC): This project seeks to develop dynamically-tunable thermal switches as a disruptive new paradigm for thermal management in buildings. Across three interrelated thrusts, the project will develop two new thermal switches, develop new tools for high-throughput measurements of low-conductivity porous materials, and conduct multiscale modeling to guide materials and prototype development.

2.2.3 Low-cost Composite Phase Change Material

(FY19-21; Multiple awardees): These eight projects will develop stable, low-cost salt hydrate and bio-based phase change materials with a focus on reducing the cost and enhancing the performance and utilization of thermal energy storage in buildings. The projects will work to address the main barriers around low cost materials utilizing novel techniques for encapsulation, stabilization, packaging, and manufacturing. These projects aim to advance the state of the art by realizing a 10x reduction in the cost of deploying PCMs for building envelopes or equipment.

2.2.4 Anisotropic Thermal Management for Building Envelopes

(FY19-21; ORNL): Finite element simulations show that the application of thermally anisotropic composites (TACs) could reduce heat gains through walls by at least 75% compared to walls with cavity and exterior insulation. TACs coupled with a thermal loop is a novel technology that can re-direct and reduce unwanted heat flows through the building envelope. This project aims to optimize the design of TAC systems for walls and roofs using lab tests, field evaluations, and calibrated models. As a conservative estimate, this project aims for 15% reductions in overall energy consumption attributed to walls and roofs. Additional capabilities of the proposed technology are shaving peak energy demand, modulating energy consumption, lowering energy use during power outages, especially during extreme heat events, and harvesting heat for water or space heating.

2.2.5 Thermal Behind the Meter Storage

(FY19-20; NREL): The objective of the project is to explore the use of thermal behind the meter storage to help facilitate grid-interactive efficient buildings. It will determine synergistic effects between thermal and battery energy storage, as well identify system tradeoffs between these energy storage systems in building applications. The project will develop the experimental protocols for characterizing thermal storage technologies at the material, component, and system level, including experiments integrating electrochemical and thermal energy storage. It will also determine the key material and component-level parameters that impact the performance of thermal storage systems and quantify the impact of these parameters. This includes material properties, component geometry, operating conditions, and how they impact cycling dynamics (charge/discharge rates), round-trip efficiency, overall load shifting capability, and ramp rates and dispatchability.

2.2.6 Model Predictive Control for Dynamic Integrated Facades

(FY17-FY20; LBNL): The objective of the project is to optimize control functions to fully utilize switchable glazings, motorized shading and daylighting systems, operable windows, and ventilation systems with predictive capability. Key driving parameters include peak electricity demand, energy savings, energy pricing, and comfort that require balancing of electric lighting and thermal loads while harvesting natural light. The work is being done in collaboration with the California Energy Commission. Over the last decade, the dynamic glazing industry has seen over 2B in private sector funding and now three suppliers have passed rigorous durability standards. The new control functions are applicable to a wide range of façade dynamic products including conventional automated shading and automated operable windows.

2.2.7 Establishment of Energy Ratings for Automated Shading

(FY18-22; LBNL/ORNL): LBNL is working to develop energy rating simulation software for a wide range of window attachments based on detailed laboratory testing that is then used by the Attachment Energy Rating Council (AERC) to establish product performance ratings for use in commercial and policy formulation. Complex geometry, shading materials, and operation schedules add to the variability and challenge. ORNL is modeling energy savings potential for automated shading for various commercial building sector applications and is collaborating with AERC to develop automated shading protocols that are essential to accurately access energy savings, grid response, and peak load reduction for individual products.

2.3 HVAC, Water Heating, and Appliances

2.3.1 Novel Solar Absorption Cooling System to Reduce Peak Loads

(FY18-FY20; ORNL): The goal of this project is to examine novel and hybrid heat pumps that could work on solar as well as electricity or natural gas to provide space conditioning and water heating in residential homes. The use of solar energy is to be the prime driver and the use of electricity or natural gas is a secondary source of energy to fulfill the needs of a residential home. The purpose is to mitigate the use of prime energy and utilize as much renewable as possible to meet demand. Liquid desiccants (LD) have the capacity to store dehumidification capacity, indefinitely, without requiring any thermal insulation. In conventional air-conditioning, the burden of latent heat removal falls entirely on the air-conditioner. If an LD is used to pre-process the air to remove the latent loads, then the energy consumption for air-conditioning is mainly limited to processing sensible loads. It is possible for LDs to remove about 70% of air-conditioning loads and lower the size and energy requirements for air-conditioning.

2.3.2 A Novel Framework for Performance Evaluation and Design Optimization of PCM Embedded Heat Exchangers for the Built Environment

(FY19-21; University of Maryland, College Park): This project will work to develop a design and optimization framework for a solid-state energy storage composite phase change material embedded heat exchanger that can improve the performance of conventional heat exchangers. The project will focus on software tool development and validation using Heat Exchanger prototypes. Results of the project could lead to a widely applicable public domain design tool for PCM HVAC use that would be useful for embedded PCM-HXs and standalone PCM use in general.

2.3.3 Grid Connected Heat Pumps

(FY19-22; PNNL): PNNL will work with Portland General Electric and the Bonneville Power Administration to measure the load shed and shifting potential of using heat pumps enabled with CTA-2045. This communication protocol allows third party implementers and/or utilities to send load shifting signals to individual heat pumps within a utility territory. This project, which is the first of its kind, aims to quantify the impact of these load shifting signals on homes in the Pacific Northwest. The goal will be to shift as much load as possible without affecting the comfort of the occupants in a discernable way.

3. Optimization of Buildings for Flexible Loads

BTO's sensors & controls and modeling portfolios focus on enabling building energy performance optimization while also considering occupant comfort. The projects related to GEB enable the ubiquitous participation of building assets in grid operations and develop technology and standards to ensure compatibility between building-facing control systems and grid-level control systems.

3.1 Analytical Inputs

In order to optimize building loads temporal and locational inputs must be included in modeling and control algorithms.

3.1.1 Weather Forecasting Projects

Site-specific weather information is crucial for operating grid-interactive efficient buildings, but it is generally unavailable or expensive to obtain.

3.1.1.1 *Spatial Temporal Data Drive Weather and Energy Forecasting*

(FY19-21, ANL): This project will develop new weather and energy forecasting algorithms with uncertainty analysis through incorporating spatial-temporal data in and around the building. The project will develop a software platform/package that includes new methodologies for site-specific weather and energy forecasting based on crowd sourcing and building operation data, and then demonstrate this platform in a real building for improved energy savings from advanced building controls.

3.1.1.2 *Machine Learning Site-Specific Weather Inference for Building Energy Forecast*

(FY19-21, NREL): This project will develop a foundational platform to provide site-specific weather forecasts by using low-cost, total-sky imagers in conjunction with readily available weather station data. This project will identify energy savings potential in GEBs by integrating: 1) Site-specific weather forecasts provided by advanced machine learning methods to capture the spatiotemporal correlations between the local weather conditions and nearby weather station data; 2) building energy forecasts from model predictive control (MPC); and 3) data analytics for evaluating the accuracy of weather and building energy forecasts, and for understanding how the site-specific weather forecasts, building types, and climates affect the energy savings in buildings.

3.1.2 Advanced Monitoring and Analytics of Building Loads

3.1.2.1 *Multi-functional Wireless Sensor Networks*

Projects awarded through the BENEFIT FY16 FOA ($4.8 million) with both universities and national laboratory performers are focused on extending the operational lifetime and automated configuration and calibration processes for wireless sensors networks in building applications with the goal of driving down the cost to enable scale-up and ubiquitous adoption.

3.1.2.2 Automated Fault Detection and Diagnostics

Leveraging prior investment and development in automated fault detection and diagnostics (AFDD), BTO is supporting several national laboratories (PNNL, LBNL, NREL, and ORNL) in the development of novel whole-building approaches for detecting and diagnosing equipment-related and control logic faults that compromise building performance and available flexibility. In addition, the team is developing a series of test procedures to establish baselines and curating datasets from which both developers and customers (i.e., building owners) can evaluate performance of new algorithms to meet specific use cases and needs. The prevalence of fault types is also being established to focus future development on opportunities that will best minimize faults that compromise building operations and provision of grid services.

3.2 Controls R&D

Projects in this area seek to develop next generation adaptive and model-predictive control systems that enable integrated, affordable, and secure control logic that interoperates across buildings, districts of buildings, and utilities while responding to occupant behavior, maximizing the quality of building energy services, and minimizing device and energy cost.

3.2.1 Optimization within Buildings

3.2.1.1 *Risk Based Framework for Dynamic Assessment and Prioritization of Flexible Building Loads*

(FY19-21; LBNL): This project will develop an open-source decision tool for commercial building operators that dynamically ranks flexible load control options based on associated risks, benefits, and operator preferences. The decision making tool yielded by this project will facilitate broader and more effective demand-response participation in commercial buildings by removing the burden of manual flexible load prioritization from building operators while retaining their response preferences.

3.2.1.2 *Hierarchal Model-free Transactive Control of Building Loads to Support Grid Services*

(FY19-21; ORNL): This project will develop a robust, scalable hierarchical transactional control mechanism incorporating elements of model-free control and game theory to harness buildings to provide grid services. This approach addresses the implementation of transactional control schemes by separating the control mechanism into two layers above and below the aggregator. The project will test the designed solution at partner sites on at least 50 buildings. During testing ORNL will measure the magnitude of grid services provided and economic incentive provided to participants.

3.2.1.3 *Comprehensive Pliant Permissive Priority Optimization*

(FY19-21; PNNL): This project seeks to build a dynamic, real-time adaptive building load prioritization framework from a selected set of influential parameters, including building function and characteristics, occupancy, operational constraints from users, time of day/year, weather, and equipment-specific safety standards and operational constraints. The framework will consist of four functional elements: 1) building load utilization and utility modeling, including a list of permissive loads to be dynamically ranked based on their utilization and their occupant-specified permissive parameters; 2) parametrized building load representation characterizing the load pliability to consumption limits; 3) integration of dynamic signals from various data sources; and 4) real-time forecast-based optimization. Together these four elements will produce a generic tool that provides real-time (with 15-minute updates) prioritization of building loads adaptive to changing user-defined operational constraints, weather, and/or dynamic grid signals.

3.2.1.4 Scalable Load Management Using Reinforcement Learning

(FY19-21; ORNL): This project will develop a cost-effective load management system (algorithm) which is easy to deploy on existing homes, can enable interoperability, and optimizes the loads to meet the homeowners' comforts and economic constraints. The scalability, performance, and accuracy of the algorithm will first be evaluated using the simulation environment that has been developed at ORNL for modeling the integrated control strategies that appear in smart grid applications. The load management system will be deployed at ORNL's Yarnell Station research house to demonstrate its performance and energy saving capabilities.

3.2.1.5 *VOLTTRON*

(FY19-20; PNNL): VOLTTRON is a communication and execution platform for connected systems, providing secure messaging and authenticated, "sandboxed" execution of specially defined software agents. VOLTTRON supports monitoring and control applications for buildings, DERs, and the grid. VOLTTRON stakeholder engagement, distribution, and requirements gathering are now managed by Eclipse Foundation. PNNL continues to support VOLTTRON with software updates, bug fixes, installation and configuration guides, and community technical assistance.

3.2.1.6 *Adaptive Controls*

(FY19-21; PNNL/ORNL): This project will develop and test advanced adaptive building controls that continuously ensure optical systems behavior in response to changing building operation conditions (e.g., outdoor air temperature and equipment performance degradation), otherwise known as adaptive supervisory control. This could eliminate the need for seasonal manual tuning of building operations and will ensure continuous automated maximization of system performance while simultaneously addressing both the variability of system loads and the uncertainty on equipment health state.

3.2.1.7 *Hot, Cold, or Just Right*

(FY19-21; LBNL): LBNL will work to provide a solution to the challenge of building overcooling: a wide-view (many-occupant) biometric comfort sensor integrated with closed-loop HVAC control. Specifically, the intent is to supplement conventional wall-mounted room air temperature sensors with a ceiling-mounted, wide-angle sensor that views the occupants. The goals are to improve occupant comfort and save cooling energy by implementing a closed-loop HVAC sensor/controller that radiatively detects occupants, occupant comfort, and room surface temperature distribution, then uses this information to reduce overcooling (cooling-energy overuse that discomforts occupants) by regulating HVAC output.

3.2.1.8 *Open Building Control*

(FY20-22; LBNL): The Open Building Control (OBC) workflow is projected to reduce building HVAC energy consumption by 20-30%. The project will develop a platform for design and specification of HVAC control sequences that interoperates with both whole-building energy simulation and automated control implementation workflows. OBC leverages Spawn, which aims to unify control design, evaluation, and optimization via whole-building energy simulation with control implementation, eliminating the manual translation steps currently associated with HVAC control implementation, reducing both error as well as effort and cost. OBC complements Spawn with a Modelica-based library of high-performance control sequences, testing and commissioning tools, and technical assistance to vendors to implement translators from Modelica to their own proprietary control platforms and products. The OBC approach will reduce the effort, cost, and error of designing, testing and deploying HVAC control sequences, while providing the industry with a formal process to test and evaluate those control sequences.

3.2.2 Optimization across a Set of Buildings

3.2.2.1 *Transactive-Control-Based Connected Home Solution for Existing Residential Units and Communities*

(FY19-21; PNNL): This project aims to overcome two barriers to large-scale market adoption of flexible building load control: 1) difficulty in integrating a new connected platform with existing home systems; and 2) lack of quantification of benefits to home inhabitants, like improved comfort, and benefits to the local utility, like grid services, resulting from connected home solutions. The project team will develop an end-to-end solution that addresses integration and cyber security. PNNL will validate the solution by quantifying the benefits such as the energy cost savings and demand reduction potentials through limited field tests. The project will provide data to show that existing homes can be cost effectively upgraded to provide grid services in the near future.

3.2.2.2 *AI Driven Smart Community Control for Accelerating PV Adoption and Enhancing Grid Resilience*

(FY19-21; NREL/SETO lead with BTO Support): This project aims to advance the building sciences on net zero energy community modeling, sensing, and control aggregating with the goal of reducing PV curtailment in the ZNE community to 0% by PV self-consumption using flexible building loads and minimal battery storage. The project outputs include: 1) advanced control method for improving load flexibility and source energy savings; 2) cost-effectiveness analysis of sensing and control devices under various utility rate structures; and 3) a report summarizing the regional differences in grid impact and savings potential of residential communities with high-penetration PV in various climate zones. During the third year, the project will conduct field testing in 20 homes to evaluate the performance of the smart community control.

3.2.2.3 Behind-the-Meter Storage (BTMS)

(FY19-21: NREL/VTO lead with BTO support): The objective of this project is to determine the design, sizing, type, and control algorithms for thermal and battery storage to maximize energy efficiency, while reducing the cost and grid impact of a grid-interactive efficient building. This project will determine the characteristics needed for new thermal energy storage materials and systems to maximize energy efficiency and solve issues arising from changing electric load and generation profiles. The analysis of the BTMS assets will focus on scenarios with standard loads, standard level 2-charging for customer vehicles, fast charging for fleet vehicles, and PV.

3.3 Building Energy Modeling (BEM) that accounts for GEB

The focus of these projects are to expand current building energy modeling capabilities to accurately represent energy demand in buildings at increasingly small timescales.

3.3.1 Spawn of Energy Plus

(FY20;LBNL): Next-generation BEM engine that reuses the EnergyPlus modules for lighting, building envelope, and loads but re-implements the HVAC and controls modules in the equation-based modeling language Modelica and is capable of supporting both traditional modeling applications as well as control design, testing, and implementation workflows. Spawn advances past EnergyPlus in several ways that are relevant to GEB: 1) it models realistic rather than idealized control sequences, correctly accounting for dynamics such as oscillation and overshoot, the control sequences themselves can be translated for direct execution; 2) it efficiently supports simulation of relevant phenomena at sub-minute time scales; ii) it supports co-simulation in a deep and intrinsic way and allows BEM to be dynamically combined with related simulations such as ones of district systems, electrical systems, and DERs; iv) its support for both co-simulation and optimization enables a range of model-predictive control implementations. Spawn is currently in the "alpha" stage, a "beta" tool is expected in late 2020 or early 2021.

3.3.2 URBANopt: District Analytics Platform for the Optimization of Building Efficiency, Flexible Loads and Storage

*(*FY19-21; NREL): The URBANopt project develops capabilities for design and optimization at the district level, combining both buildings and shared systems including DERs, micro-grids, and shared thermal systems. URBANopt leverages Spawn/OpenStudio and adds Modelica-based district system

modeling capabilities as well as Application Programming Interfaces (APIs) for integration with other simulations including DERs (FEMP's REopt), distribution systems (EPRI's OpenDSS), storage, and micro-grids. The project includes a private sector partnership to integrate the new capabilities into a user-facing tool and to use URBANopt in several active district redevelopment projects. This project will determine how buildings can be designed and optimized within a district in conjunction with DERs and the electric utility distribution system and explore the associated value propositions.

3.3.3 Deep Reinforcement Learning for GEB

(FY19; NREL): The project will overcome the shortcomings of the state-of-the-art by leveraging the emerging deep machine reinforcement learning (RL) paradigm. It will extend previous work on deep RL as well as previous efforts in the literature on RL control systems for buildings and will develop scalable multi-objective RL algorithms that will simultaneously address both building-centric and grid- serving objectives. All this will be achieved without the need for detailed and accurate building models by virtue of the RL methodology and will be replicable to heterogeneous buildings. The algorithms will be tested in simulation and compared to the model predictive control (MPC) algorithms that are based on detailed and accurate models.

3.4 Cybersecurity

Leveraging investments in adaptive controls and their advantages over rule-based approaches, new efforts are underway to optimize control strategies against attacks and to develop cyber-resilient controls that adaptive and capable of maintaining continuity of operations when compromised. Furthermore, investments in AFDD are being leveraged for detecting and diagnosing faulty equipment operation or control logic resulting from cyber-related attacks and vulnerabilities**.**

3.4.1 Adaptive Cyber-Physical Resilience for Building Control Systems

*(*FY19-22; General Electric Company [GE]): This project will advance adaptive cyber-physical resilience for building control systems by employing a reinforcement learning-based adaptive model predictive control architecture to ensure safe and near-optimal closed-loop operation under all identified cyber-fault scenarios.

3.4.2 Securing Grid-interactive Efficient Buildings (GEB) through Cyber Defense and Resilient System

(FY19-22; Texas A&M): This project will help secure GEBs with a novel cyber defense and resilient system (a real-time building platform with cyber-attack-immune capabilities) by pursuing multi-layer prevention, detection, and adaptation.

3.4.3 Building Intelligence with Layered Defense using Security-Constrained Optimization and Security Risk Detection (BUILD-SOS)

(FY19-22; University of Central Florida): This project will develop an integrated cyber-physical threat awareness, layered defense, and fault and attack-tolerant control solution for building energy management systems using Security-Constrained Optimization and Security Risk Detection (BUILD-SOS).

4. Validation & Verification of Building Performance for Grid Services

The focus of this work is lab and field verification & validation of building technology performance and controls optimization for a grid-interactive efficient building.

4.1 Component & Systems Validation & Verification

4.1.1 Grid Connected HPWHs

(FY18-22; PNNL): PNNL will work with stakeholders in the Northwestern and Southeastern parts of the U.S. to measure the amount of load that can be shed and shifted by HPWHs using field validation in real homes. Building off of previous work, PNNL will help DOE answer questions like, "Can more energy be shifted using smart algorithms (compared to running conservative events for the whole population of water heaters) to predict human behavior at any given time without sacrificing the comfort of the occupants?" and "How different is the load shed and shifting potential of HPWHs in the SE vs. the NW of the U.S.?"

4.1.2 Validation of a Co-optimized, Smart Hybrid Heat Pump Control for Energy and Cost Savings, Peak Load Management, and Grid Resiliency

(FY20-22; Newport Partners): This project will develop, validate, and optimize advanced controls for hybrid heat pumps (HHP), an electric heat pump and gas furnace, in cold climate existing homes. The project will examine one prototype home under varying scenarios and will improve the viability of dual fuel heat pumps based on control optimization for cost, energy savings, peak demand and carbon emissions. It will also evaluate mixed-fuel utility regions (efficiency, demand control, and renewable energy integration) as well as apply the results to other regions and building types through modeling.

4.1.3 Technology Analysis & Validation of Integrated Connected Lighting, Auto Shading and Intelligent Storage for GEB

(FY19; Slipstream): The project will validate high density sensor (lighting, shading) integration with Building Automation System (BAS) to reduce overall peak lighting and integrate hybrid roof top units (RTU) with thermal storage (Phase Change Materials [PCM] with wax and graphite) for a shift in two field sites (office or higher education buildings). Slipstream will partner with a local utility partner that will assist with field sites recruitment. The project will incorporate an integrated system control for GEB (shed, shift) with and without thermal storage. The Calibrated Building Energy Models will include rate structures for field sites varied by climate zone and control strategies across prototype buildings.

4.1.4 Standardized Field Validation Protocols and Performance Data for EMIS Technologies

(FY19-21; LBNL): This project aims to develop standardized field validation protocols and datasets for energy management information system (EMIS) software analytics technologies. This work has significance with regards to the development of utility programs, investments by building owners, and future R&D. The protocols will cover all aspects of performance assessment including new hardware needs, data integration efforts, energy and demand savings, maintenance savings, and reporting savings. After the project team develops the standardized protocols, they will conduct EMIS validation projects and release the results to the public via DOE's Building Performance Database (BPD).

4.1.5 Building-Level DC Distribution Systems

(FY19-21; NREL/LBNL): Since power is delivered through an alternating-current (AC) system and most electrical-powered equipment runs on direct-current (DC), each device in a building requires an AC-to-DC converter. Besides these converters in devices, buildings with on-site photovoltaic systems and battery storage may require several additional conversions between DC and AC. These conversions and other system inefficiencies account for energy losses between 2% and 18%. Using DC distribution systems in buildings represents an opportunity to reduce losses and realize significant energy and cost savings. This project will test DC distribution systems in real buildings in order to establish DC-system evaluation methods and metrics, document real-world performance, and assess technical barriers inhibiting robust adoption of these systems. The project team will also report on opportunities for improved performance through better integration and development of new technologies

4.1.6 Commercial Buildings Integration Lab

(FY20; NREL): The ESIF commercial building lab will provide a research platform taking advantage of hardware-in-the-loop functionality for grid-interactive efficient buildings specifically in three key focus areas: flexibility for demand side management, intelligent efficiency, and interoperability (connectivity, controls, communication). This flexible laboratory space will include the electrical infrastructure to emulate three commercial buildings and will connect to ESIF infrastructure including megawatt scale photovoltaic array and grid emulators used to simulate different grid or renewable energy sources. The lab will include hardware-in-the-loop capabilities to drive HVAC systems and simulate any building components that are not physically represented in the lab to reduce the risk of new technology integration for utilities and building owners.

4.1.7 Incentivizing Cold-climate Efficiency in Juneau

(FY20-22; Cold Climate Housing Research Center [CCHRC]): CCHRC will validate energy savings and fuel displacement using energy efficiency (EE) retrofit package in Juneau, Alaska. The study will include 50 households receiving EE retrofits, 50 households receiving heat pumps only, and 50 households receiving EE retrofit packages and heat pumps. The EE package will likely include: LED lights, air sealing, insulation, window attachments, and hot water reduction. CCHRC will provide package specific training for installers and investigate bulk purchasing with finance options to incentivize future retrofitting. The project will evaluate increased electric heating without impact on the electricity grid load and compile a guide for replication.

4.1.8 Hardware-in-the-loop Laboratory Performance Verification of Flexible Building Equipment in a Typical Commercial Building

(FY19-22; Drexel University): This project will produce publicly-available, high-fidelity datasets that measure the holistic load flexibility performance of a suite of commonly-used commercial building HVAC and thermal storage equipment.

4.1.9 A Framework to Characterize the Performance of Flexible Loads and Building Services Using a Hardware-in-the-Loop Approach

(FY19-22; LBNL): This project will measure building equipment performance and impacts on building services using advanced testing capabilities with cutting-edge modeling tools.

4.1.10 A Scalable Hardware-and-Human-in-the-Loop Grid-interactive Efficient Building Equipment Performance Dataset

(FY19-22; Northeastern University); This project will create a GEB equipment performance dataset using new occupant-centric control algorithms that produce grid services from heat pumps.

4.2 Validation & Verification across a Set of Buildings

4.2.1 Smart Neighborhoods Research & Field Verification

(FY19-21; ORNL): This project will develop, demonstrate, and validate a scalable control framework to co-optimize energy cost, occupant comfort, grid reliability and resilience in next generation neighborhoods that integrate renewable energy sources and energy storage solutions. This includes home level and aggregated neighborhood level load optimization and forecasting. The framework will facilitate communication of aggregated load status and forecast with a micro-grid controller and engage in a transactive market with the micro-grid to optimize loads versus micro-grid assets. The aggregator will in turn communicate load response needs to the individual house and adjust major home loads (HVAC and water heating) accordingly. These projects are performed in partnership with Alabama Power and Georgia Power.

4.2.2 Scaling of Building Transactive Control and Coordination to Support Grid Operations a.k.a The Campus Project

(FY19-21; PNNL): This project will develop and demonstrate an open source, scalable, transactive control system (hardware and software) that enables both existing and new buildings to provide grid services without decreasing utility. It addresses a key gap which must be overcome to enable buildings to cost effectively provide grid services at the necessary scale to be impactful. This project will result in an automated agent-based control method for prioritizing controllable end-use loads for peak load management, dynamic load shaping and transactive control. Demonstration will be achieved by forming a multi-campus network using a layered transactive control and coordination approach that is tailored for low-cost embedded computers. The project will result in a published template for replication of transactive control and coordination of flexible building loads at scale.

4.2.3 GT-FLEX Atlanta

(FY20-21; NREL): This project will validate the performance of optimized controls across 12-18 existing education buildings on the Georgia Tech campus for the existing HVAC system, battery and thermal energy storage. The project evaluation will include peak load reduction, the ability to shift energy, and return on investment.

BTO collaborated with the General Services Administration (GSA) to release a Request for Information (RFI) in FY20 focused on validating building technologies and energy services that can cost effectively provide building load flexibility as part of a GEB strategy. Several GSA and Better Building partner sites will be utilized to validate performance pf selected GEB solutions over multiple years.

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