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**Authors**
Langner, Rois
Granderson, Jessica
Crowe, Eliot

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# Quantifying the Value of Grid-Interactive Efficient Buildings through Field Study

***Rois Langner, National Renewable Energy Laboratory***
***Jessica Granderson and Eliot Crowe, Lawrence Berkeley National Laboratory***

**ABSTRACT**

Quantifying the annual energy impacts of efficient technologies in commercial buildings has been well established by the building science field. As we move toward enabling grid-interactive efficient buildings (GEB) targeting flexible building operation and carbon reduction, quantification methods to evaluate time-sensitive peak load and emissions impact are much less defined. A number of national laboratories are working to field validate four different GEB software solutions that provide the capability to control multiple building end-use systems in multiple load flexibility modes (i.e., energy efficiency, load shed, load shift, and possible load modulation at the second to sub-second level). To guide the laboratory leads in effective measurement and verification (M&V) practices, two of the laboratories collaborated to define metrics to quantify the impacts of flexible load control on building demand, utility costs, carbon emissions, facility management, and occupant comfort. This paper summarizes the proposed metrics to quantify peak load and emission impacts in the field, decision parameters, approaches to accurately conduct M&V, lessons learned, and outstanding needs and next steps.

## Introduction

### Grid Interactive Efficient Buildings

Grid-Interactive Efficient Buildings (GEBs) are energy efficient buildings that can smartly respond to time-dependent grid signals in a flexible manner [DOE 2019a]. Using analytics and controls to optimize building energy for occupant needs, weather, utility price signals, and available on-site generation and storage, GEBs aim to integrate and continually optimize behind-the-meter distributed energy resources (DERs). DERs, in this sense, go beyond onsite solar and battery storage to include energy efficiency, demand response, and integrated electric vehicles [DOE 2019a]. Flexible load operation can be provided by all of these DERs and many building end-use systems through the following modes [DOE 2019b]:

- Energy efficiency: ongoing reduction in energy used while providing improved building function,
- Load shedding: the ability to reduce electricity use for a short period of time and typically on short notice,
- Load shifting: the ability to change the timing of electricity use,
- Load modulation: the ability to balance power supply/demand or reactive power draw/supply autonomously (within seconds to sub-seconds) in response to a utility signal, and
- Generation: the ability to generate electricity for on-site consumption and even dispatch electricity to the grid in response to a grid signal.

### Advanced Controls and Emergence of GEB Software Solutions

Energy Management and Information Systems (EMIS) have been on the market for many years. They support the identification and implementation of operational improvements in commercial buildings [Lin et al. 2021]. These software solutions integrate and organize building data from multiple end-use systems, conduct data analytics, recommend actionable information to the building engineer, and continually monitor performance and measure savings [Lin et al. 2021]. EMIS platforms have optimized certain aspects of HVAC operation for lowest cost, lowest consumption, and/or managing monthly peak demand based on utility tariffs. GEB software platforms extend this functionality to more modes of operation, more end-uses, and by responding to utility signals.

In July of 2020, the U.S. General Services Administration (GSA) along with the U.S. Department of Energy's (DOEs) Building Technologies Office (BTO) jointly selected four GEB software solutions for field demonstration through the GSA Proving Ground (GPG) and DOE High-Impact Technology (HIT) Catalyst programs [GSA 2020]. The National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), Pacific Northwest National Laboratory (PNNL), and Oak Ridge National Laboratory (ORNL) were selected to lead measurement and verification (M&V) efforts of the selected GEB software solutions to be demonstrated in both federal and private-sector buildings.

### Quantifying GEB Impacts

Flexible load operation provides an enormous benefit to many electrical grid challenges, including managing peak demand capacity, mitigating utility system peak increases due to major electrification strategies, and integrating variable renewables. While metrics to quantify annual energy impacts of energy efficient technologies in commercial buildings have been well established by the building science field, quantification methods to evaluate the impact of flexible load operation on energy consumption, peak demand, and emissions are much less defined. LBNL has worked extensively on defining metrics for evaluating demand flexibility [Liu 2020]. However, applying these metrics to the real-world GPG and HIT Catalyst GEB field demonstrations required development of an M&V evaluation plan template. Developed by NREL and LBNL with input from PNNL, the template provides instructions for characterizing GEB software solutions, outlines considerations for site selection, and provides guidance for evaluating quantitative and qualitative GEB objectives and metrics. This paper summarizes these metrics and considerations for wider distribution to other GEB M&V teams.

## GEB Characterization

GEB software solutions come with a variety of functionality and business cases. It's important to characterize the solutions before implementing them to understand their full functionality and potential impact to the building, and to support M&V Plan development. Table 1 below provides a list of questions that were addressed prior to deploying the four GPG/HIT Catalyst demonstration projects, along with additional guidance that should be considered to characterize a GEB software solution.

Table 1. GEB Characterization

| GEB Characteristic | Additional Guidance |
|---|---|
| Targeted end-uses that the technology addresses | Specify: lighting, HVAC, refrigeration, water heating miscellaneous electric loads, process loads, on-site generation, and/or energy storage |
| End-use systems or technologies that are required for implementing the solution | Specify end-use systems or technologies such as HVAC, on-site generation, storage, specific sensors, etc. that are required for successful operation of the solution |
| Demand flexibility modes supported | Specify: efficiency, shift, shed, modulate, and/or generate |
| Does the technology accept 1- or -2-way communication from the grid? | Yes/No |
| Communication protocol used by the utility to communicate with the technology | Examples: OpenADR, IEEE 2030.5, proprietary |
| Grid-interactive control: the intelligence or logic that the technology implements to adjust behavior to provide grid response | Specify: (1) Static: vendor-defined modes including default control sequences; (2) Programmable: user-defined responses to grid signals, pre-programmed; or (3) Optimized: the system combines grid signals with functional goals to determine operation |
| Impact of grid-interactive control on building services | The effect that providing grid services has on building services, such as light level, hot water temperatures, space temperatures, or ventilation rates. Responses should indicate impact level: none, minimal, or significant |
| Energy penalty: additional energy required to deliver grid services relative to the baseline energy[1] | This can be negative. Responses should indicate the percent of energy penalty compared to the baseline energy (e.g.: 3% energy penalty) |
| Additional technology capabilities if applicable | This can include non-energy benefits that the solution offers. For example, with vendor-specified sensors, the GEB solution can interface with door locks for security purposes. |
| Cybersecurity measures | This includes accounting for all efforts required to ensure that all Information Technology components of the vendor's solution meet documented Federal and GSA-specific IT Security standards within an established time frame. |
| Pricing structure | Note pricing structure from technology provider. |

## Site Selection Considerations

[1] For example, shifting load may result in an overall increase in kWh consumed, while providing significant grid and/or carbon benefits based on when the energy is being consumed.

Capturing building site characteristics is necessary for any demonstration project. When evaluating a GEB software solution, it's important to consider both general site characteristics as well as characteristics pertaining to end-use systems that can be controlled in a flexible manner, the building automation system (BAS), any distributed energy resources (DERs) that may contribute to or be impacted by load flexibility, and utility rate structures. A summary of recommended site characteristics to capture is presented in Table 2 below.

Table 2. Site Characteristics

| **Site Characteristics** |
|---|
| Location |
| Year built |
| Primary/secondary building use |
| Building floor area that will be impacted by controls |
| Occupancy schedule |
| Building energy use intensity (EUI) [kBtu/ft$^2$/yr] |
| HVAC system description (System type, configuration, # units, etc.) |
| Describe other controlled end-use systems such as lighting that may be relevant to the GEB demonstration. |
| Describe any customer-sited DERs that are relevant to the GEB demonstration |
| BAS description (make, model, communication protocols) |
| Utility rate structure (describe the tariff) |
| Energy improvements or capital projects within the last 2 years |
| Retro-commissioning projects within the past 5 years |
| Key site selection attributes (why was this site chosen?) |

## Detailed Methods for Measurement & Verification

The following sections provide detailed instruction on how to approach M&V for GEB solutions, focusing on evaluation of three of the five load flexibility modes: energy efficiency, load shed, and load shift. Load modulation is excluded as it is more beneficial to the utilities than building owners, and the GEB software solutions selected for the GPG and HIT Catalyst demonstrations did not offer this capability. Renewable generation is considered in the demonstrations, with on-site solar photovoltaic (PV) generation present at some of the demonstration sites, but is considered only as an offset to building energy consumption. Calculating the impacts of energy efficiency, load shed, and load shift, are more complicated and explained in detail in this paper.

For each performance objective, or group of objectives, descriptions of the following should be noted:

1. The sensor/meter data and building characteristic data that will be collected to quantify the metrics in Tables 3 and 4. This should include the:
    a. Quantity of data (such as whole building electricity, HVAC electricity, local outside air temperature, site-specific utility tariffs, etc.),
    b. The measurement of data (e.g., 15-minute interval data),
    c. The level of measurement (whole building, submeters, area-local, etc.), and

    d. The source of the data, which could be from on-site meters, site-provided information, reports from site operations staff, or external sources such as weather or utility data.
2. The primary evaluation method that will be used. This could include surveys or interviews of the site staff, occupants, or providers, project tracking records, analysis of sensor or meter data, or calculations based on other performance objectives (e.g., cost savings due to efficiency, payback, etc.). Additional considerations include:
    a. For all methods, document assumptions that could significantly impact the results or values of computed metrics based on the specific methods planned.
    b. For methods based on surveys or interviews, provide the specific questions in your documentation.
    c. For methods related to continuous demand management, peak load shed and load shift, note whether tariffs and/or events will be emulated or implemented in response to existing tariffs and programs that the site is enrolled in.
    d. For methods based on analysis of sensor or meter data, discuss as applicable:
        i. The International Performance Measurement and Verification Protocol (IPMVP) [EVO 2022] option(s) used for energy and demand savings, and any guidance from resources such as ASHRAE Guideline 14 [ASHRAE 2014], Bonneville Power Administration (BPA) M&V guides [BPA 2018], or others.
        ii. Baseline time horizons (e.g., the year prior to implementation, the 10 days prior to an event, etc.).
        iii. Baseline model formulations (e.g., weather regression with specified form and variables, weather matching, etc.)
        iv. Performance period over which metrics will be calculated (e.g., 9-12 months for overall energy efficiency savings, 14-days of load shed events, 6-months of tariff-induced shift, etc.).
        v. Any breakout of metrics for different seasons or operational modes (e.g., occupant comfort during DR events vs. "overall" or "standard" operations).
        vi. Any normalizations or extrapolations required to estimate annual consumption totals from partial monitoring periods.

## Quantitative Performance Objectives & Success Metrics

Table 3 summarizes the quantitative GEB solution performance objectives and success metrics. Methods to evaluate each objective are described in the following subsections. It should be noted that both quantitative and qualitative performance objectives and success metrics should be considered for GEB M&V projects. Energy saving technologies are unlikely to hold adoption if there are negative impacts to occupant comfort or if the technology is challenging to operate. Thus, it is important to assess qualitative performance objectives as well. Recommended qualitative performance objectives are discussed in the following section.

Table 3: Quantitative GEB Solution Performance Objectives/Success Metrics

| **Quantitative Objectives** | **Metrics** |
|---|---|
| Energy-Efficiency Savings (whole building savings from GEB solution and not any supplemental 'static' | Energy savings: kWh/yr and % savings<br><br>Energy intensity savings: kWh/ft$^2$/yr |

| | |
|---|---|
| energy conservation measures[2]; component level savings should be specified in final report) | |
| Continuous Demand Management | Monthly peak demand reduction: kW and %<br><br>Monthly demand charge reduction, site-specific and GSA-average<br><br>Summer and winter seasonal average peak kW reduction<br><br>Summer and winter seasonal average demand charge reduction $ |
| Peak Load Shed | Demonstrated load shed<br><br>a. Demand shed per event: Average kW reduction (for shed) over a specified time window<br>b. Average % demand reduction<br>c. Demand shed intensity: kW/ft$^2$<br><br>Consistency of load shed: Provide a range of average kW, or whisker-box plots showing the distribution of load shed for temperature bins, with bin sizes determined by actual temperature conditions of each shed event. |
| Load Shift | Average (over shift days summer/winter) demand decrease/increase: kW, W/ft$^2$, %<br><br>Net building energy consumption change in 24 hours: (over shift days summer/winter) %<br><br>Consistency of load decrease/increase across each day of shift (summer/winter) |
| Greenhouse Gas Emissions Reduction | Annual CO2eq reduction: kg $CO_{2eq}$ /yr<br><br>Normalized annual kg $CO_{2eq}$ reduction: kg $CO_{2eq}$/ft$^2$ /yr |
| Cost Savings | Cost savings due to efficiency and peak demand charge savings: $/year<br><br>Cost savings due to load shed/shift: $/year<br><br>Simple payback: |

[2] For example, a supplemental 'static' energy conservation measure could include an uncontrollable LED lighting retrofit that happened concurrently.

| | |
|---|---|
| | a. If all costs are in the first year (e.g., no recurring licensing/software costs):<br>simple payback [yr] = price [$]/cost savings [$/yr]<br><br>b. If there are recurring annual costs, report the break-even point [yr] at which first year savings [$] are equal to accumulated costs:<br>first year savings [$] = first year total cost [$] + annual cost [$/yr] * break even [yr] |

**Energy Efficiency:**

Energy efficiency savings (including gas if controls apply to gas equipment) should be quantified by calculating the difference in energy consumption between baseline and implementation periods using whole-building hourly or sub-hourly interval data for electricity and gas. For analyses that require simulation modeling, for example, in situations where building operation is interrupted for a period of time, additional facility characteristics and equipment operational information will also be needed

Whole building, annual energy savings will be calculated in kWh/year, percent energy reduction, and energy use intensity (kWh/$ft^2$/year). It will be up to project teams to determine if it's appropriate to report targeted energy savings associated with specific building end-use systems as well.

The IPMVP defines four generic M&V approaches for determining energy savings. Options B through D should be considered for M&V [EVO 2022]. Option A is not applicable for controls-focused measures. Descriptions of Options B through D include:

- Option B - Retrofit Isolation with All Parameter Measurement,
- Option C - Whole Building Utility Data Analysis, and
- Option D - Calibrated Computer Simulation.

Under this protocol, the recommended savings estimation method for determining annual energy savings is to follow Option C or Option B, which determines savings impacts based on actual metered data. Option D (simulation) may be required if metering is not available or cannot be conducted.

In addition to the IPMVP, several other guidelines (ASHRAE Guideline 14 [ASHRAE 2014], BPA Verification by Energy Modeling Protocol [BPA 2018b], BPA Regression for M&V reference guide [BPA 2018c]) provide additional detailed guidance on the application of meter-based Option B and Option C approaches. Furthermore, LBNL's EMIS Field Evaluation Protocol v2.0 provides guidance in evaluating similar control software [Lin 2021].

**Continuous Demand Management (Utility Demand Charge Reduction):**

Utility demand charge reductions should be quantified using monthly utility bill statements, the demonstration site's specific tariff, and – as an additional consideration, a national average peak demand charge structure could be used. The primary analysis methods should comprise analysis of as-billed peak demand charges throughout the period of the demonstration, compared to a baseline of peak demand charges the year prior to the demonstration. The structure of peak demand charges can vary from simpler to more complex and a deep dive into these structures is recommended.

For each month of the demonstration period and the baseline period, the following should occur:

- Identification of billed peak demand charges and the corresponding maximum load.
- The reductions in maximum load and demand charge should be calculated as the difference between the baseline values and the demonstration values (baseline - demonstration).
- The percent reductions in maximum load and demand charge should be calculated as the difference between the baseline values and the demonstration values, divided by the baseline values {(baseline - demonstration)/baseline}.
    - The monthly reductions and percent reductions can be binned seasonally based on the summer/winter months defined in the tariff.
    - The average monthly demand charge and maximum load reduction can be calculated for each season.

Results can be documented to show monthly as well as average seasonal values (summer and winter as defined by the utility). Additionally, an analysis of the change in weather conditions between the baseline and demonstration periods can be conducted to provide context for the findings. Weather normalization should be conducted where valuable and where robust methods are available.

This methodology assumes a constant tariff structure and rates between the baseline and demonstration years. If this assumption is not in alignment with the building, the methodology should be revised accordingly.

**Peak Load Shed (Demand Response) and Load Shift:**

Peak load shed and load shift should be quantified using whole-building hourly or sub-hourly interval electricity data, and variables such as outside air temperature that will be required for a baseline model. For analyses that require simulation modeling (e.g., due to impacts from COVID-19), additional facility characteristics and grid interactive technology operational information will also be needed.

The primary evaluation method should comprise the analysis of sensor or meter data according to the principles of IPMVP Option C, or analysis of calibrated simulation data according to the principles of IPMVP Option D. Load shed and shift should be quantified relative to a baseline, and metrics should be calculated and reported for each season in which the load flexibility modes were implemented.

The baseline time period should comprise days prior to the days on which load was shed or shifted. The specific number of days and selection of days that form the baseline period will be defined according to the constructs that are used in the demonstration region, territory, or programs. If no programs exist, California constructs could be considered as a default [Bode 2017]. The specific form of the baseline model (e.g., day matching, weather matching, time of week and temperature regression, use of pre-event adjustments) will also be aligned with that currently in use in the demonstration region, territory, or programs, again with California constructs used as a default if none exist.

For each day of shed or shift, metered load during the flexibility time window is subtracted from the baseline load to determine the magnitude of demand increase or decrease for each metered time interval. Additionally, the following calculations should be made:

- The magnitude of shed/take in each time interval should be averaged over the duration of the shed or take period to determine the daily kW impact.
- The daily kW increase or decrease should be divided by square footage to determine the daily kW/sf impact.
- The daily kW increase or decrease should be divided by the average load during the flexibility window to determine the percent impact.
- The net building consumption change percentage is the net total kWh consumption increase or decrease measured against a 24-hour baseline encompassing the shed or shift window and any pre-event and post-event demand level changes (e.g. rebound effects), then divided by the baseline total kWh consumption during the same 24 hours.

The daily values of each metric should then be averaged across all days for which the load flexibility was demonstrated to determine the reported shift and shed metrics. Calculations can be repeated for each season in which the flexibility was demonstrated. Additionally, the consistency of load shed can be reported by showing a range of average kW, or whisker-box plots, showing the distribution of load shed for temperature bins. Temperature bin sizes should be determined based on actual temperature conditions of each shed event. This representation will then show a range in expected kW for various temperature conditions and can be interpreted for seasonal impacts. Lastly, it's useful to report the percent occurrence of the shed events during each specified season.

Documentation of results should note the hours of the day that formed the shed or shift window for each season, and the number of days over which the shift or shed was demonstrated in each season. It should also note whether the shed or shift was conducted in response to actual demand response (DR) programs or time-of-use (TOU) tariffs, or whether it was conducted using emulated ("mocked-up") programs or tariffs.

**Greenhouse Gas Emissions Reduction:**

To calculate greenhouse gas (GHG) emissions reduction, electricity energy savings (hourly savings across a whole year since this will be linked to hourly utility emissions for the building's regional generation mix) and gas energy savings (annual savings, since GHG emissions associated with natural gas usage do not vary by time of day/year) should be used. The primary evaluation method will use emissions factor data to convert energy reductions into avoided carbon emissions. Direct emissions reductions from gas and other fuels will be summed with indirect avoided emissions from reductions in electricity use.

For gas and other fuels, convert natural gas and other fuels' annual savings into carbon dioxide equivalent ($CO_{2eq}$) reductions by applying direct GHG emissions factors for the U.S. and Canada based on the Energy Star Portfolio Manager Technical Reference on Greenhouse Gas Emissions [ENERGYSTAR 2020]. Multiply the annual fuel savings [MBtu/yr] by the associated emissions factor [kg/MBtu $CO_{2eq}$] to determine the annual reduction [kg $CO_{2eq}$ /yr]. Then divide the annual reduction [kg $CO_{2eq}$ /yr] by the building floor area to determine the annual reduction intensity [kg $CO_{2eq}$ /ft$^2$/yr].

$CO_{2eq}$ reductions (kg CO2eq) associated with electricity savings can be estimated by multiplying hourly load reductions by the corresponding hourly non-baseload emissions factors specific to the region in which the project site is located. A couple data sources for hourly non-baseload $CO_{2eq}$ emissions include:

- NREL's Cambium long run marginal emissions rates (Mid-case) [NREL 2021]
- A fee-based marginal emissions dataset, such as those available through WattTime or WattCarbon [WattTime 2022, WattCarbon 2022]

Other emission reduction calculator tools were explored in this research, including the Environmental Protection Agency's (EPA's) Avoided Emissions and geneRation Tool (AVERT) and EPA's Emissions & Generation Resource Integrated Database (eGRID). However, these tools and databases are not currently suitable for accurately evaluating the emissions reduction of GEB operation in a single building but may be added as a potential data source if updated at a future date [EPA 2022].

If using the Cambium dataset for $CO_{2eq}$ reduction estimates, it is suggested to calculate and report levelized long run marginal emissions using a 10-year evaluation period and default discount rate (0.03). Additional evaluation periods and default rates can also be explored. If using a fee-based marginal emissions dataset, calculate annual emission reduction estimates using historical data corresponding to the M&V data time period.

To calculate the total emissions reduction, sum the annual $CO_{2eq}$ reductions from gas or fuel and electricity savings to determine the total carbon reductions [kg $CO_{2eq}$ /yr] and reductions in site carbon intensity [kg $CO_{2eq}$ /ft$^2$/yr]. In addition to providing total annual $CO_{2eq}$ reductions, hourly reductions (kW and kg $CO_{2eq}$) associated with electricity could also be captured.

**Cost-Effectiveness:**

Cost effectiveness can be evaluated using utility-specific tariffs and incentives, energy and demand savings, and the providers' technology cost information. Technology cost information is supplied by the technology provider. Cost savings will have several components. Annual volumetric energy savings [$/year] can be calculated by summing the volumetric monthly gas and electricity savings, multiplied by the gas and electricity costs as defined in the site's utility tariff. Savings should be normalized to a full year if the performance period is shorter than twelve months. Annual peak demand charge savings can be calculated by summing the monthly peak demand charge savings and normalized to a full year if the performance period is shorter than twelve months.

Load shed or other grid service incentives [$/year] can also be calculated. Sites participating in existing incentive programs can report incentive payments based on actual settlements. Sites emulating participation in existing or hypothetical programs should estimate their would-be incentives based on demonstrated load flexibility as quantified in Peak Load Shed (Demand Response) and Load Shift, an assumed number of days per year of participation, and an assumed incentive level. All estimates must be justified based on existing program examples, incentive levels, and dispatch histories. Documentation of all assumptions and estimates is helpful. Please note that if a project chooses to update their rate plan because of a field study, savings attributed to both the original and new rate plans should be included.

## Qualitative Performance Objectives & Success Metrics

Table 4 summarizes the qualitative GEB solution performance objectives and success metrics. Methods to evaluate each objective are described in the following subsections.

Table 4: Qualitative GEB Solution Performance Objectives/Success Metrics

| **Qualitative Objectives** | **Metrics** |
|---|---|
| Ease of Installation/Commissioning | Calendar duration required for installation and commissioning (days starting at contract notice to proceed "NTP" where vendor is cleared to work in the building)<br><br>Labor hours required of site staff [days]<br><br>Building owner/facility manager experience installing and commissioning (host site interviews, score on 1-5 Likert scale 1 being worst, 5 being best) |
| Occupant Comfort | Change in space conditions during occupied hours, based on the end uses/services affected in the control strategy (e.g., ventilation, lighting), for a sample of zones:<br><br>a. Thermal comfort: % increase/decrease in hot/cold calls, and/or % increase/decrease within/out of comfort range (e.g, simplified ASHRAE model based on temperature, relative humidity, winter/summer).<br><br>b. Visual comfort: change in accepted ranges of interior illuminance levels [%]<br><br>c. Indoor air quality: change in accepted ranges of interior $CO_2$ levels |
| Operator Acceptance | A facility manager & operation and maintenance survey and interviews including (using 1-5 Likert scale) addressing:<br><br>a. Level of skill and/or position required to operate the solution (describe the position level needed to operate the solution and any additional training that is required)<br><br>b. Satisfaction with the operator interface(s) (1-5 Likert with 1 not satisfied at all, 5 being highly satisfied |

| | |
|---|---|
| | c. Satisfaction of implemented load flexibility control strategies (1-5 Likert with 1 not satisfied at all, 5 being highly satisfied)<br><br>d. Satisfaction of shift and shed controllability responding to dynamic signals (i.e., changes in rate structure, seasonal changes, etc.)<br><br>e. (Optional) Number of system overrides (or recommendations rejected), normalized by a site-specific factor such as number of events, or hours of operation. |

**Ease of Installation/Commissioning**

Ease of technology installation and commissioning should be evaluated using project tracking records, as well as surveys or interviews with demonstration site staff. To quantify the calendar time required for installation and commissioning, the starting date should be determined in agreement with the evaluator, site point of contact (POC), and GEB technology provider. The end date should be the first day of technology operation, following all verification activities, at which point the GEB technology provider should be ready to begin the performance period to quantify benefits. The reporting units for installation and commissioning should be total days (including weekends).

As an optional reporting metric, labor hours required for installation and commissioning can be reported as well, in units of days; however, it may be difficult for site POCs to accurately estimate this. If possible, site POCs can be interviewed to estimate how much staff time was required to support the installation and commissioning process (excluding time for IT staff for controls contractors).

The demonstration site POC's overall experience getting the technology installed and commissioned can be evaluated using a 5-point Likert scale survey or interview question, with 1 representing the most negative experience, and 5 representing the most positive experience.

Where applicable, the installation and configuration time can be broken into subphases specific to the technology being implemented, e.g., initial installation, learning or tuning, or operator verification.

**Occupant Comfort**

Occupant comfort should capture thermal, visual, and air quality impacts, as appropriate to specific controls that are being implemented. Thermal comfort can be evaluated using a simplified model based on temperature and relative humidity for winter and summer months, and facility data collected on hot or cold calls. For projects where lighting is impacted, lighting level data and facility data related to visual complaints can be used. For projects where air quality is impacted, data from $CO_2$ sensors can be used.

Changes to space conditioning during occupied hours should be evaluated based on the end uses or services affected in the control strategy for a sample of representative zones. Thermal comfort can be evaluated by looking at the percent increase or decrease within or out of comfort range (e.g., simplified ASHRAE model based on temperature and relative humidity) for winter and summer months. Facility data on hot or cold calls can also be used to calculate a percent increase or decrease to hot or cold calls during occupied hours within a season.

If lighting is impacted, visual comfort can be calculated using interior illuminance levels in a sample of representative zones. A percent increase or decrease in illuminance levels can be calculated. Additionally, if visual complaints are being captured by the facility, record the percent increase or decrease in these complaints during winter and summer seasons.

Lastly, if ventilation is impacted, $CO_2$ sensors can be placed in a sample of representative zones to evaluate the percent change in accepted ranges of interior $CO_2$ levels.

### Operator Acceptance

Operator acceptance can be evaluated using project tracking records, as well as surveys or interviews with demonstration site staff. Record the level of skill and/or position, and any additional training, required to operate the solution. Note whether the solution required more or less skill than expected or portrayed by the vendor.

Operator acceptance can be quantified by administering a survey or interview to understand operator satisfaction with the solution's user interface, ability to implement load flexibility controls, and ability to easily change or update load flexibility controls in response to dynamic signals such as sudden changes to occupancy, unexpected weather, seasonal changes, utility rate changes, etc. Operator satisfaction can be evaluated using 5-point Likert scale survey or interview questions with 1 being not satisfied at all and 5 being highly satisfied.

As an optional metric, the number of system overrides or rejected control recommendations that were delivered by the solution can be quantified. Determine and apply a site-specific normalizing factor, such as the total number of GEB (or load flexibility) control events, period of evaluation, or hours of operation in which the events might occur.

## Discussion

The M&V methods presented in this paper pull from a mix of well-established methods, such as IPMVP, and emerging practices to best quantify the impacts of flexible load operation. The demonstration projects through the GPG and HIT Catalyst programs, and other related efforts, will help to refine these methods as we move forward and more GEB projects are evaluated.

A few gaps and opportunities can be highlighted. In isolation, there is a large amount of confidence in each evaluation method presented here. However, the aim of a true GEB is to have dynamic load optimization with frequent load shaping and GEB modes operating concurrently. There is a need for continued innovation on how to evaluate multiple building end-use systems operating in multiple load flexibility modes simultaneously to more holistically capture the impact of GEB operation. Programs such as GPG and HIT Catalyst that provide good quality empirical data are critical in enabling refinements in this optimized operation and evaluation of impact.

Building upon the evaluation methods presented in this paper, methods to evaluate load modulation could be added. In addition, as GEB software solutions evolve to more strategically integrate and dispatch generation and storage, better evaluation methods for this integration could be developed. Other demonstration programs, such as those through the DOE Connected

Communities Funding Opportunity, could be leveraged to refine evaluation methods [DOE 2020].

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