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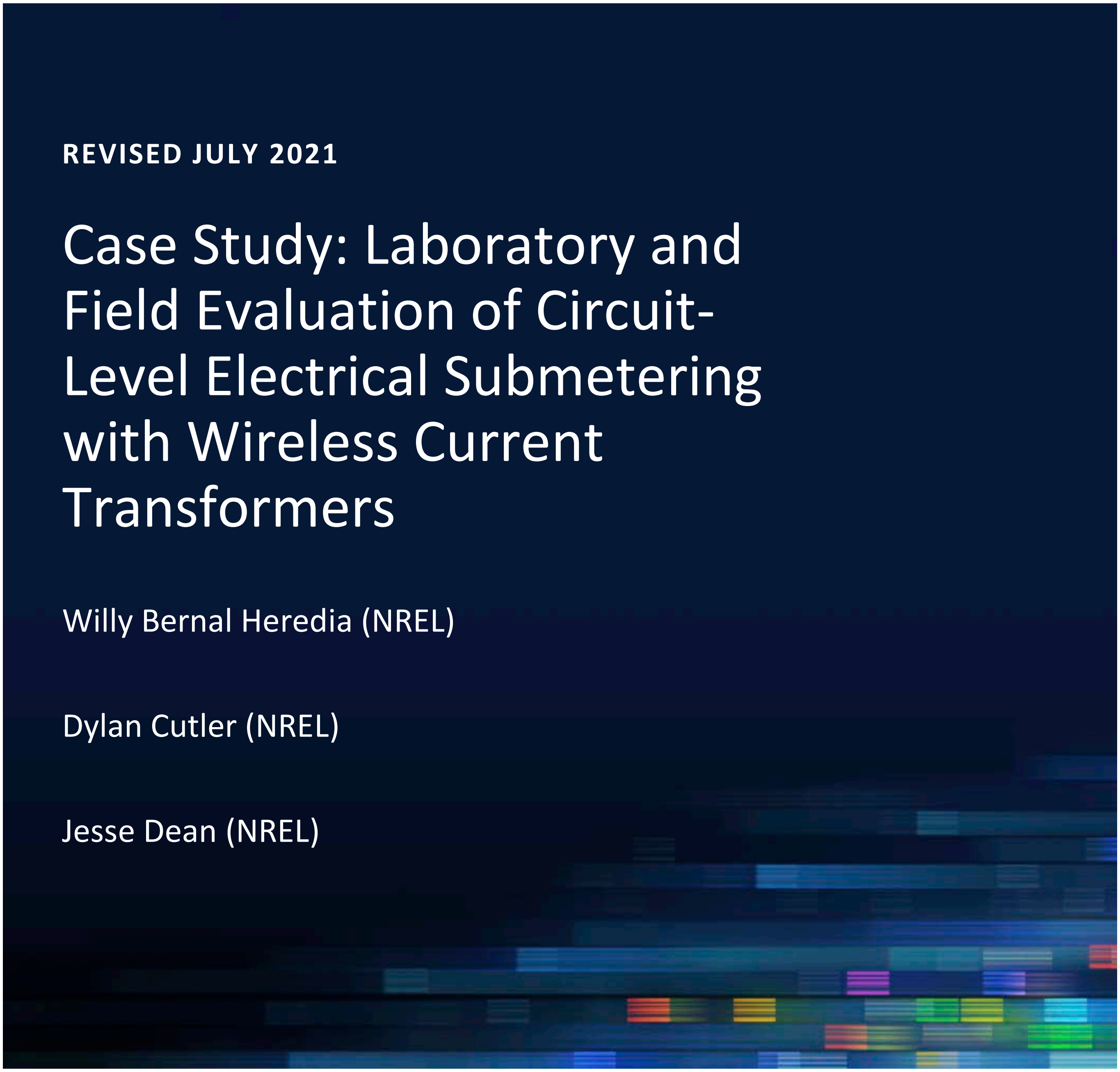

REVISED JULY 2021

Case Study: Laboratory and Field Evaluation of Circuit-Level Electrical Submetering with Wireless Current Transformers

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Addendum

This report, originally published in June 2019, has been revised in July 2021 to note a corrected software issue.

After the field evaluation concluded, Centrica (formerly Panoramic Power) detected a software bug in their automated export service used to collect the data for this report. The power measurements directly from the PAN-42 were not being conveyed but calculated using a default power factor value ($P = V * I * PF_{default}$), as opposed to the metered one. Centrica has fixed the auto exporter problem; this issue only affected the PAN-42 data and did not compromise the wireless current transformers' (CTs') data (PAN-10, PAN-12, and PAN-14). In short, the discrepancy was not inherent to the hardware or measurements but connected to the export process. During the time of the original deployment, NREL determined the PAN-42 meter's energy error at 7%, while the expected results were 2% or less.

To reassess the accuracy of the meters, NREL conducted a laboratory demonstration in 2020 at its Commercial Building Research Integration Facility and assessed the performance of the circuit-level submetering technology in three commercial building panels. The primary goal of the demonstration was to confirm that the accuracy of the circuit-level submetering matches the manufacturer's claims (<2% error) after the software bug was resolved.

During the laboratory validation, NREL installed the PAN-42 in one 120/208V and two 277/480V panels, and verified that the circuit-level submetering system under evaluation can measure accurately, record, and store all claimed electrical quantities.

NREL evaluated the three-phase meter connected to three loads: one refrigeration case (120V), one pump (480V), and one chiller (480V). The latter two were controlled by variable frequency drives (VFD). NREL used a Campbell Scientific revenue-grade meter for verification. Figure A-1 contrasts the measurements (power, current, voltage, and power factor) between the reference meter and the PAN-42 for the 30-ton commercial scroll chiller. Table A-1 summarizes the findings for the evaluation.

Centrica improved their meters' accuracy significantly from the field deployment—the measurements for power, current, and voltage met or exceeded expectations (<2% error). Those measurements matched closely the reference meter and can provide highly accurate readings for large loads (>5A). The PAN-42 uses non-proprietary CTs, so NREL ensured that the analyzed data met or exceeded the threshold where the CTs' accuracy is guaranteed; the non-proprietary CTs only provide high accuracy (<1%) above 10% of its rated capacity. Only the chiller met this threshold of 10A (100A-rated CTs). The pump and refrigeration case drew less than 5A (50A-rated

CTs) and did not meet that requirement. The average power error for the chiller was 1% whereas for the pump and refrigeration case it was 4% and 7% respectively. NREL cannot determine whether the increased error for the pump and refrigeration case can be attributed to the Centrica meters or the CTs. Accuracy results for all loads are presented in Table A-1.

Power factor readings produced larger errors (11%) for the chiller. This was attributed to the large harmonic distortion caused by the VFDs; the total harmonic distortion for current reached 100%. This is expected for systems with VFDs because of the rectification and inverter stages. Related measurements to power factor, such as reactive power, produced large errors (~90%) for the VDF loads.

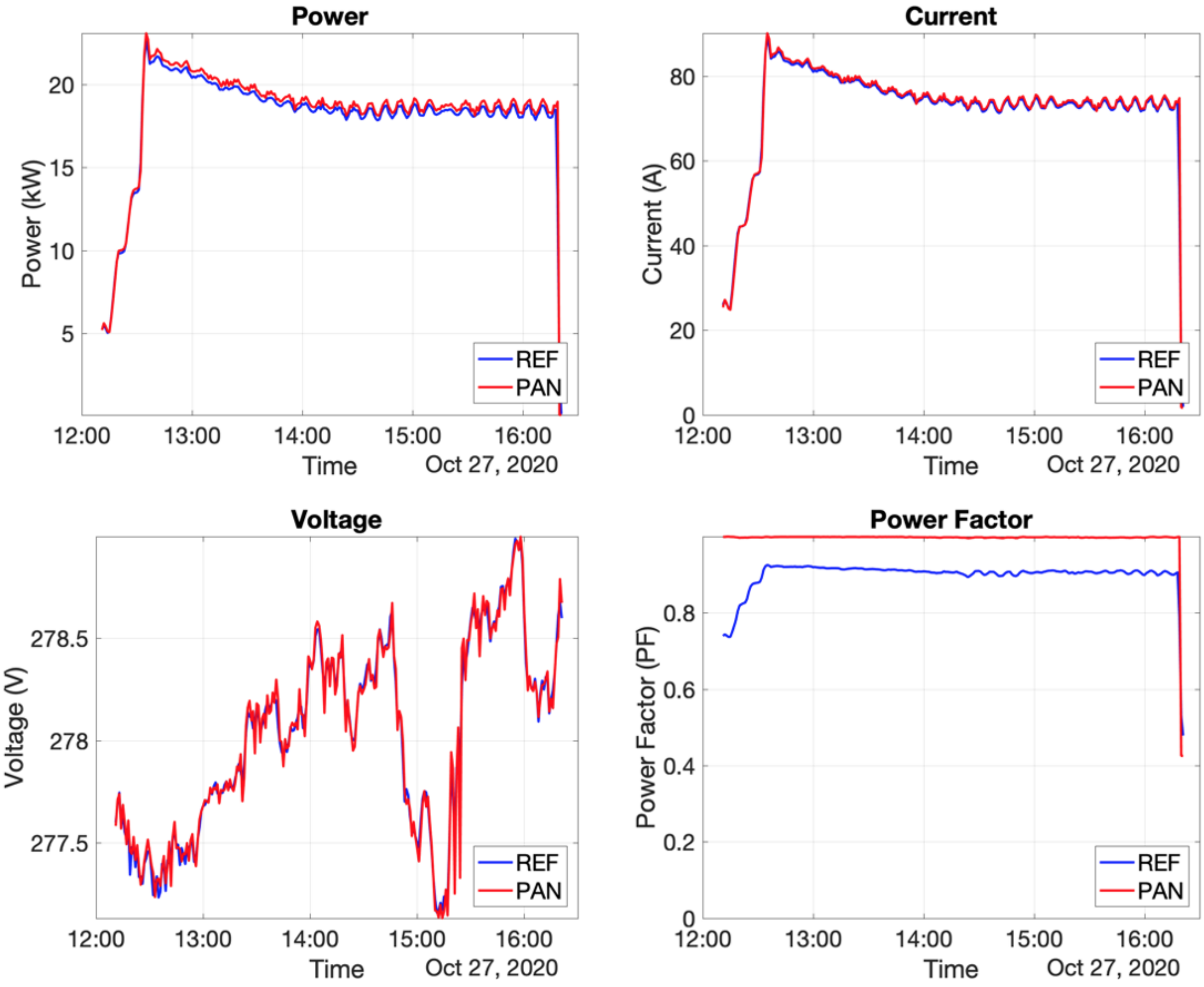

Figure A-1. Chiller measurements for revenue-grade meter (REF) and the Pan-42 (PAN)

Power factor is a measure of how effectively electricity is used in a system; a power factor lower than 1 means that part of the electrical energy is not doing useful work, but rather lost through heat. Power factor is seldom used but required during power factor corrections applications, where low power factors are undesirable and can be penalized by the utility.

The PAN-42 requires 5A current-output CTs (vs. voltage-output CTs). The current-output CTs are only usable down to around 50A without multiple turns on the primary winding, so low current levels usually lead to degraded accuracy. On the other hand, voltage-output CTs can accurately measure down to fractions of an amp (depending on the design). These CTs can be adjusted to generate highly calibrated signal voltage output for precision measurement.

Table A-1. Accuracy Results During Laboratory Validation

Parameter	Equipment	Avg. Error (%)	RMSE (%)	Total Energy Error (%)
Power	**Chiller (VFD)**	**1.52**	**1.55**	**1.56**
	Pump (VFD)*	**4.05**	**4.79**	**4.76**
	Refrigeration case*	**-7.27**	**10.11**	**-1.72**
Current	**Chiller (VFD)**	**0.57**	**0.73**	
	Pump (VFD)*	**-6.34**	**6.34**	
	Refrigeration case*	**-6.57**	**7.63**	
Voltage	**Chiller (VFD)**	**0**	**0**	
	Pump (VFD)*	**-0.14**	**0.14**	
	Refrigeration case*	**-0.06**	**0.06**	
Power Factor	**Chiller (VFD)**	**11.98**	**12.85**	
	Pump (VFD)*	**77.15**	**77.16**	
	Refrigeration case*	**51.7**	**57.22**	

Parameter	Equipment	Avg. Error (%)	RMSE (%)	Total Energy Error (%)
Reactive Power	**Chiller (VFD)**	**-89.28**	**89.28**	
	Pump (VFD)*	**-88.22**	**88.22**	
	Refrigeration case*	**11.98**	**12.85**	

***Loads did not meet 10% threshold of CTs’ ratings**

In short, the PAN-42 accurately measured (<2%) power, current, and voltage only above 5A due to the nature of its compatible current-output CTs. Errors below 5A can increase up to 7%, but NREL could not determine whether that increase could be attributed to the meter or the non-proprietary CTs. Power factor and reactive power did not track closely for loads with large harmonic content (e.g., VFD controlled). The meters provided a streamlined approach and user-friendly alternative to collect data from large commercial loads (e.g., large HVAC equipment or panel mains). Power factor and related quantities did not track well with the revenue-grade meters because of high distortion content from the VFDs. VFD adoption is relatively small but is becoming more popular because of its benefits: energy efficiency, intelligent motor control, and reduction of peak-current drawn. To successfully deploy these meters, caution must be exercised in identifying the characteristics of the load (e.g., current ratings and total harmonic distortion) to ensure applicability and desired accuracy. Since the original project, Centrica has updated its pricing information. Table A-2 shows those updates.

Table A-2. Updated Centrica Pricing

Equipment	Types	Details	Cost
PAN-10 and PAN-12	Wireless CTs	No meter needed, only the bridge is required for installation.	$141
PAN-42	Meter compatible with wired high-accuracy CTs	In addition to the meter, non-proprietary CTs are required (1 CT per phase/$40 each).	$282
Bridge V 4+ LTE	Gateway with cellular modem capabilities	The bridge can communicate and pair with up to 250 devices (meter or wireless CT). No service included.	$389

Disclaimer

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GSA's Proving Ground (GPG) program enables federal and commercial building owners and operators to make sound investment decisions in next generation building technologies based on their real-world performance.

Executive Summary

Circuit-level analytics and submetering platform (CLASP) technologies provide the ability to monitor individual circuits within an electrical panel in a building, providing detailed power and energy consumption data at a much more granular level than was previously achievable in a cost-effective manner. While the fundamental hardware components of CLASP—split-core current transformers (CTs) and power monitoring meters—have existed for some time, the new offerings in the market have tightly integrated these components and have streamlined data organization, transport, and access via software solutions accessible through web and application programming interfaces.

Building owners and operators typically have a difficult time accessing data on electrical power and energy consumption within the building. They may have access to whole-building electrical data via advanced metering infrastructure (AMI), but very rarely do they have insight into the power and energy consumption of individual end uses or devices. This lack of visibility into electrical data limits the ability to identify issues with individual pieces of equipment, quantify consumption of specific end uses or tenants, or present occupants with accurate data about their own energy consumption as building users. CLASP facilitates various innovative use cases, such as tenant billing, tenant engagement, measurement and verification (M&V), automated fault detection and diagnostics (FDD), identification of energy conservation measures (ECM), time-of-use management, and demand response.

Evaluation of this technology focused on three aspects of the CLASP technology: (1) accuracy of the data provided by the system, (2) ease of installation of this technology and ease of data integration into existing U.S. General Services Administration (GSA) analytics platforms, and (3) ability of the data to be used to drive energy savings and the cost-effectiveness of the technology. The specific performance criteria outlined for this demonstration, as well as success criteria and results of testing, are outlined in Table ES-1.

The CLASP technology analyzed in this study was the circuit monitoring system developed by Panoramic Power. This CLASP technology was tested in a laboratory setting on a residential electrical panel at the National Renewable Energy Laboratory (NREL) as well as in a field deployment where it was installed in a variety of commercial electrical panels in the César E. Chávez Memorial Building in Denver, Colorado. The field demonstration portion of the project focused on assessing the metering accuracy, the value proposition of the technology, and its potential for deriving energy savings from identifying ECMs or fault detection.

This technology proved easy to install by a certified electrician who completed the install of 144 meters in 13 separate panels and 4 circuit disconnects (along with associated commissioning) at the César E. Chávez Memorial Building in less than one day. The technology was installed in high- and low-voltage panels and with limited space in the electrical room, demonstrating the applicability of this technology to almost all commercial buildings in the GSA portfolio. Primary considerations for this technology include appropriate sizing of CTs for each circuit (e.g., PAN-10, PAN-12, or PAN-14), selection of loads/circuits/panels that are of high value for detailed submetering (e.g., tailored for high-load devices and fault detection), and how GSA would like to integrate these data with its existing energy management infrastructure.

Through the field evaluation, we demonstrated data integration from the CLASP system into the primary software component on the GSA enterprise-level energy management and information system, GSA

Link. Data from the CLASP were integrated into this platform and used to perform FDD. This demonstrated the ability of CLASP to augment existing energy management and information systems in buildings where GSA Link is deployed and provides a pathway for delivering FDD at other buildings throughout the portfolio.

Although the accuracy measured during this field evaluation did not meet the success criteria outlined for accurate in-field consumption data listed in table ES-1, we showed that CLASP was able to provide high-resolution power and energy consumption data that can provide insights into equipment operation and support the value propositions outlined in Table ES-1. Total energy error was greater than the 10% success criteria for some, but not all, loads, and large errors were frequent in loads with heavy cycling and non-unity power factor (e.g., root mean squared percent error [RSMPE] of 9%–33% for some variable air volume [VAV] equipment). The total energy error was consistently lower than 10% for the lighting loads (see Table 8). The wireless CTs are self-powered and require a minimum amount of current to turn on and record data. Thus, the CLASP could not record low readings in the 0.5–1 A range. Both available CLASP configurations were tested on a three-phase transformer for 3 months—one requiring a voltage tap (PAN-42) and one only requiring CTs (PAN-14)—to assess whether the voltage tap configuration would provide required accuracy for tenant billing. The accuracy was not increased considerably; the total energy error for the transformer went from 7.15% to 7.03% after using a voltage tap during the 3-month period.

Table ES-1: Performance Objectives

Quantitative Objectives	Metrics and Data Requirements	Success Criteria	M&V Results
Submeter Accuracy in Laboratory Environment	• Current • Voltage • Power • Power factor • Energy	• Measurement accuracy of +/- 2% at full scale for Panoramic Power (1% for PAN-42)	Not Met – Did not meet criteria. Total energy error was above 5% for all tests.
Submeter Accuracy In-Situ Field Demonstration	• Current • Voltage • Power • Power factor • Energy	• Measurement accuracy of energy consumption (as cumulated over 2–4 weeks) of +/- 10% • Measurement accuracy of +/-10% for total power measurements[1] • 99.9% data availability over the course of the demonstration	Not Met – Total energy error was <10% only for certain low-variability loads.
Qualitative Objectives			
Ease of Installation and Integration with GSA Information Technology (IT)/Enterprise Systems	• Level of technical expertise required • Time required to install and configure • Customer labor associated with install • Data integration requirements • Security requirements • Ease of visualizing and downloading data	• Ability to be installed in the majority of GSA's electrical panels. • Ability to integrate into GSA Link infrastructure. • Generally applicable to >70% of GSA facilities	Met – Successfully and efficiently installed in a variety of panels. Demonstrated integration in software components of GSA Link.
Value Proposition and Cost-Effectiveness	• Installation and operations and maintenance (O&M) cost • Energy and cost savings identified • Value of tenant billing • Value of FDD	• Potential savings exceeds expected installation and O&M costs • Software offers measurement and analytics capabilities that address industry needs	Met – Technology demonstrated ability to identify relevant behavior (e.g., cycling, on/off, seasonal trends) and capability to be life cycle cost-effective.

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[1] Evaluation of meter accuracy during laboratory testing demonstrated that comparison to stated accuracy in product literature was not appropriate for field testing success criteria. Accuracy values in product literature were developed using controlled voltage/current sources and are not reflective of in-field operation and, therefore, should not be the success criteria for this objective.

		- Data from software can be utilized to identify a significant portion of the faults and ECMs identified by the GSA Link software (75% or more) - Determine if life cycle is cost-effective as a standalone platform	

Figure ES-1 shows the time series data for two devices (a lighting load and a VAV system) with very different characteristics in the field demonstration. This figure demonstrates how well the CLASP was able to track the power signal of the device (red trace), as compared to the revenue-grade submetering installed by NREL (green trace). In the right graph (VAV), the CLASP was unable to read low-power levels and would show as 0 kW and also show a consistent offset during on periods.

The data obtained from the CLASP helped identify ECMs and other operational issues. One of the identified ECMs was to turn off one of the two central chillers during non-cooling months. The potential savings for this single ECM could deliver an estimated 87% of the energy cost savings required to make the CLASP system life cycle cost-effective for the entire building, (assuming a typical installation cost for a 180,000 ft^2 building). This finding highlights the ability of this technology to identify ECMs, monitor the savings delivered by addressing those issues, and provide savings that may offset the capital and recurring costs of the system.

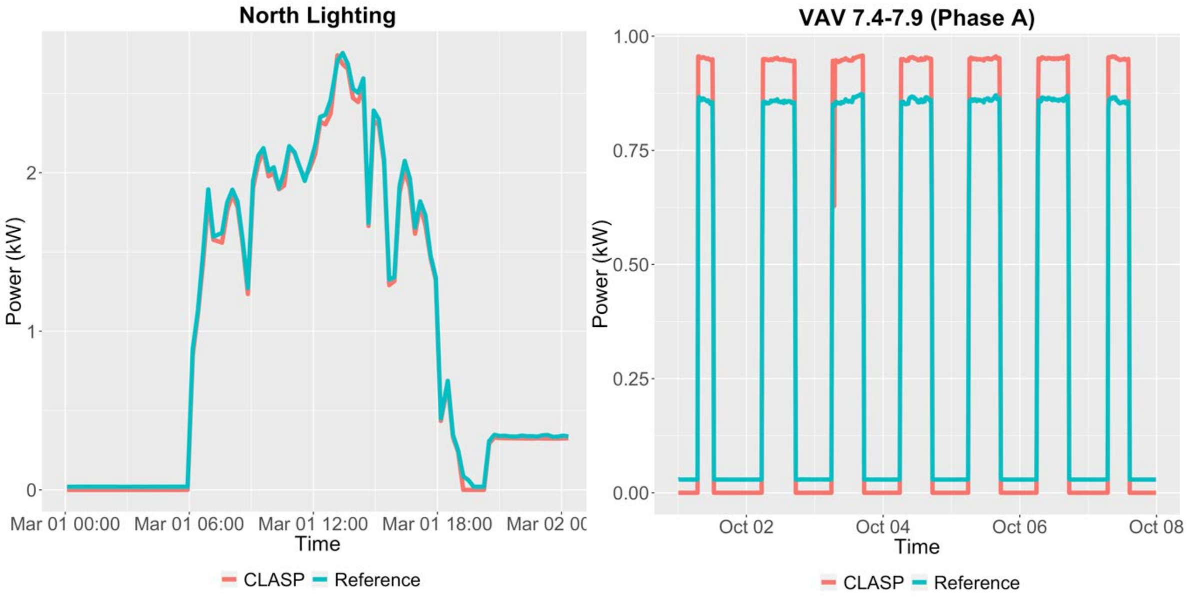

Figure ES-1: Accuracy results for two devices in the field demonstration. One day of lighting data is shown in the left figure and a whole week of a VAV device operation in the right figure.

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I. Introduction

A. WHAT WE STUDIED

This report evaluates a hardware/software technology solution that provides a circuit-level analytics and submetering platform (CLASP) in buildings. This technology was tested in a laboratory setting and in a field deployment where it was installed in a variety of electrical panels in the César E. Chávez Memorial Building in Denver, Colorado.

CLASP is a fast-growing technology area. New products continue to be developed that allow building owners and operators to gain increased insight into the electrical consumption of their facility at significantly reduced costs compared to the incumbent technology and approaches. This legacy technology corresponds to standard metering such as the Campbell Scientific equipment (WattNode[2]) that provides high accuracy at the expense of longer installation time, higher costs, and larger form factor. This report describes this standard technology in more detail in Section II.C.ii. CLASP technologies typically use split-core current transformers (CT) to measure the current flowing through the electrical wiring. Readings from the CT are combined with voltage readings from the electrical panel (or user input voltage values) to calculate the power consumption of the devices. These data are then transmitted to a data historian that is hosted either locally or in the cloud. Data transport methodologies vary—methods include Wi-Fi, cellular, and ethernet—and systems keep varying amounts of data locally on hardware or bridges as a buffering mechanism for any network interruptions in delivering data to the larger data historian. These data are then made accessible to the user through some form of user interface, typically a web interface. Web interfaces provide a variety of data analytics offerings, varying from simple data access/visualization to development of rule-based alarms to complex benchmarking and fault detection and diagnostics (FDD) algorithms. Many companies also support programmatic access to the data via an application programming interface (API).

The CLASP technology analyzed in this study was the circuit monitoring system developed by Panoramic Power. This system provides a highly compact data acquisition system consisting of CTs and a wireless communication bridge that can collect data from up to 250 CTs. In contrast with other systems, the Panoramic Power system features metering systems that do not require a voltage tap. However, they offer a voltage tap solution for applications that require higher accuracy (PAN-42). Table 1 and Table 2 show the specifications on the CLASP system: CTs and bridge device.

The CLASP system features wireless CTs that are powered through the electromagnetic field generated from the electrical lines they are measuring. A wireless communication channel exists between the CTs and the bridge, which is placed outside the panel. To ensure good connectivity, the bridge is mounted in the vicinity of the electrical panel where individual loads or circuits are to be measured. Split-core CTs are installed in the electrical panel. The lack of wiring and conduit enables a rapid installation process, reducing the installation time and disruption to a minimum. For the CTs to be powered up and transmitting data, a minimum of approximately 1 A needs to be flowing through the wire. In the case of

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[2] The WattNode is a kilowatt-hour (kWh) energy and power meter that measures 1, 2, or 3 phases with voltages from 120 to 600 volts Vac and currents from 5 to 6,000 amps. https://ctlsys.com/product/wattnode-modbus/

the PAN-42, voltage taps are connected from the monitoring system to the electrical panel and provide voltage measurements for the power calculations as well as power to the monitoring system.

The CLASP system transmits 1-minute data (calculated from an approximately 10-second sampling at the sensor level) to the cloud, where the data are stored and made accessible through the vendor's web-based analytics platform. The system also supports a RESTful API for programmatic data access. This hardware and software suite represents a streamlined set of components where the data processing, calculations, and local data storage are all housed in small form factor equipment and where the installation is streamlined via the limited, plug-and-play components (Figure 1).

Table 1: CLASP CT Sensors

Characteristic	PAN-10	PAN-12	PAN-14	PAN-42
Description	Wireless Current Transducers			Wireless Meter
Service Type	Single-Phase, Three-Phase			
Measurement Type	Current (A)			Current (A), Voltage (V), Power Factor, Frequency (Hz), Power (kW, kVA, kVAR)
Transmission Frequency	10 seconds			
Current Measurement Range	1–63 A	1–225 A	1–maximum amperage of selected CT	0–maximum amperage of selected CT
External CT Required	No	No	Yes	Yes
Input Power	Self-Power			External Power

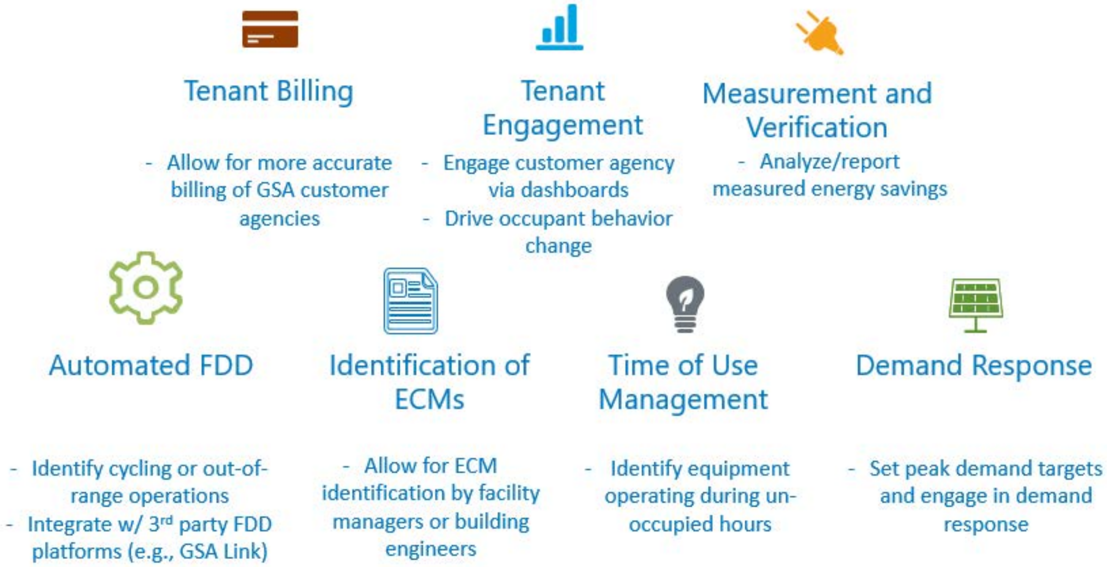
Table 2: CLASP Bridge Specifications

Characteristic	Description
Input Channels Per Bridge	250 Sensors
Storage	10 CTs – 10 Days 20 CTs – 5 Days 100 CTs – 1 Day 200 CTs – 0.5 Day
Communication	SIM Card Slot

B. WHY WE STUDIED IT

Building owners and operators typically have a difficult time accessing data on electrical power and energy consumption. They may have access to whole-building electrical consumption data via advanced metering infrastructure (AMI), but very rarely do they have insight into the power and energy consumption of individual end uses. This lack of visibility into electrical data limits the ability to identify issues with individual pieces of equipment, quantify consumption of certain end uses or tenants, and present occupants with accurate data about their own energy consumption as building users.

CLASP provides the ability to monitor power at each electrical circuit in the building, providing insight into different types of end-use consumption (e.g., plug loads, lighting loads, or heating, ventilation and air-conditioning [HVAC]), specific device-level consumption, or the floor- or panel-level consumption within a building. CLASP allows for various innovative use cases, such as tenant billing, tenant engagement, measurement and verification (M&V), automated FDD, identification of energy conservation measures (ECM), time-of-use management, and demand response. A listing of each value proposition and a brief description is provided in Figure 2.



Tenant Billing
- Allow for more accurate billing of GSA customer agencies

Tenant Engagement
- Engage customer agency via dashboards
- Drive occupant behavior change

Measurement and Verification
- Analyze/report measured energy savings

Automated FDD
- Identify cycling or out-of-range operations
- Integrate w/ 3rd party FDD platforms (e.g., GSA Link)

Identification of ECMs
- Allow for ECM identification by facility managers or building engineers

Time of Use Management
- Identify equipment operating during un-occupied hours

Demand Response
- Set peak demand targets and engage in demand response

Figure 2: CLASP value propositions

CLASP does not save energy directly but rather is an enabling technology that allows for more thorough and comprehensive energy management than is possible without the insight it provides. The enhanced visibility of specific end-use or device-level energy consumption and the analytical insights provided by this technology promise to be more granular and scalable than data delivered by traditional submetering.

Standard approaches to submetering in buildings have been either tailored AMI deployment or custom installations of circuit-level submetering. AMI is typically installed at the whole-building or large end-use (e.g., chiller plant) level and utilizes utility-grade, solid-state meters. Federal agencies and other large organizations have been increasingly installing electrical meters and associated communications and data storage equipment as a part of AMI deployment in the last two decades. AMI installations at federal facilities typically consist of installing a revenue-grade whole-building interval electrical meter, gas meter, steam meter, or water meter that collects 15-minute or 1-hour interval data. The data from the AMI meters are communicated through local area network (LAN), the building automation system (BAS), radio frequency, or wireless network communication to a central database. The high cost of deploying AMI, ranging from few to several thousand dollars per meter (including installation), and its applicability to individual large loads does not allow for detailed submetering within a building. The incumbent approach to submetering specific loads within a building has been to build up a system from individual components—including CTs, meters, data loggers, and data communications devices—and install them for the loads under consideration. Traditionally, this approach has led to high costs on a per-point basis and does not easily scale to measure all loads within a building(s). The new developments in CLASP—streamlined or integrated hardware and data hosting/analytics solutions—are driving costs down and warrant investigation into the quality and cost-effectiveness of these new solutions in the marketplace.

When evaluating the different value propositions that CLASP offers, three main value propositions were identified that were of interest to the U.S. General Services Administration (GSA):

1. Evaluation of building energy performance and improvement in building operations, including identification of ECMs and FDD
2. Acquisition of accurate, high-resolution data and using those data as drivers for energy savings associated with occupant behavior change (e.g., tenant incentive programs)
3. Acquisition of accurate, high-resolution data for the purpose of tenant billing.

CLASP in general, and the vendor technology specifically, are at technology readiness level (TRL)[3] 8. The products have been tested in an operational environment, are at a complete design phase, and are available in the market. This demonstration effort verified that the final systems perform as expected in the field environment, assisting in completing the transition to TRL 9.

II. Evaluation Plan

A. EVALUTATION DESIGN

Evaluation of this technology focused on three aspects of the circuit-level submetering technology: (1) accuracy of the data provided by the system, (2) ease of installation of the technology and ease of data integration into existing GSA analytics platforms, (3) ability of the data to be used to drive energy savings and the cost-effectiveness of the technology.

i. Accuracy

We assessed data accuracy in two separate environments: in a controlled laboratory deployment in the Energy Systems Integration Facility (ESIF) at the National Renewable Energy Laboratory (NREL) and in a field deployment in a commercial building. In each of these cases, the circuit-level submetering was installed on circuits within an electrical panel(s) that captured a variety of end uses and a range of power demand magnitudes. To quantify the accuracy of the data acquired by the circuit-level

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[3] TRLs are a method of estimating technology maturity of Critical Technology Elements. The DOE defines their own TRL. Please refer to https://www2.lbl.gov/dir/assets/docs/TRL%20guide.pdf

submetering, we installed high-fidelity, revenue-grade submetering on the same set of circuits as the CLASP technology under evaluation. Data were collected simultaneously from the circuit-level submetering and the revenue-grade metering, allowing for assessment of the accuracy provided by the system.

Successful performance in the accuracy evaluation portion of this demonstration was evaluated via two quantitative objectives:

Quantitative Objective 1: Submeter Accuracy in Laboratory Environment

- Success criterion: The technology demonstrates the ability to operate within the manufacturer's specified accuracy range in a controlled laboratory environment (measurement accuracy for current, voltage, and active energy: +/- 1% at full scale [PAN-42] and current: +/- 2% [PAN-10 and PAN-12]).

Quantitative Objective 2: Submeter Accuracy In-Situ Field Demonstration and Associated Data Availability

- Success criteria:
    - The technology demonstrates the ability to provide energy and power data of sufficient accuracy to enable identification of ECMs and to enable the quantification of savings due to those ECMs. Technology demonstrates purported data storage capabilities. Measurement accuracy is +/-10% for total power measurements.
    - The technology provides sufficient data availability to function effectively in a tenant billing system (99.9% data availability over the course of the demonstration).

ii. Ease of Installation/Integration

The second goal of this demonstration was to evaluate the ease of installation of CLASP technology and the ease of data integration into existing GSA analytics platforms. Ease of installation and ease of use are key considerations for energy submetering technologies because labor costs associated with installation and use may exceed the cost of the hardware. To assess this objective, we participated in the installation process for the submetering system, documented the level of effort and process that was taken for install, and interviewed the GSA staff or contractors installing the product.

Additionally, we worked with the GSA Link team to assess the possibility of the CLASP data to be integrated into their enterprise energy management and information system. GSA Link is an analytics platform that GSA uses to evaluate performance of its buildings, track issues, and initiate work orders for project execution. The ease of installation and integration was assessed via the following qualitative objective:

Qualitative Objective 1: Ease of Installation and Ease of Integration with GSA Link System

- Success criterion: The ability of the technology to be installed in the majority of GSA's applicable electrical panels and the ability to be integrated into GSA Link architecture.

iii. Cost-Effectiveness

The final evaluation criteria for this demonstration was an evaluation of the cost-effectiveness of the technology. Assessment of this criteria is challenging because there are no energy savings directly related to the acquisition of high-quality data. These data must be acted upon to derive savings from this technology. Additionally, the opportunities for savings may be vastly different between different buildings or different equipment that is measured using the metering technology. To provide some insight on the cost-effectiveness of this technology, we evaluate the amount of savings that must be delivered to offset the technology cost.

To ensure that we could test this objective (at least in this specific technology demonstration site), NREL analyzed the type of ECMs that could be detected with the CLASP system. Additionally, the CLASP vendor produces a quarterly report on issues identified by its system and the energy and operational efficiency of the building based on the sensor readings. These reports contribute to the evaluation of the ability of the technology to assist in driving energy savings. This portion of the assessment was evaluated by the following objective:

Qualitative Objective 2: Value Proposition and Cost-Effectiveness Analysis

Success criteria:

- The technology demonstrates a clear value stream that would enable cost-effective installation and incorporation into GSA Link.
- The technology demonstrates a clear value stream that would enable cost-effective installation and use as a standalone platform.

Table 3 summarizes the performance objectives for this demonstration.

Table 3: Performance Objectives

Quantitative Objectives	Metrics and Data Requirements	Success Criteria	M&V Results
Submeter Accuracy in Laboratory Environment	• Current • Voltage • Power • Power factor • Energy	• Measurement accuracy of +/- 2% at full scale for CLASP (1% for PAN-42)	Not Met – Did not meet criteria. Total energy error was >5% for all tests.
Submeter Accuracy In-Situ Field Demonstration	• Current • Voltage • Power • Power factor • Energy	• Measurement accuracy of energy consumption (as cumulated over 2–4 weeks) of +/- 10% • Measurement accuracy of +/-10% for total power measurements[4] • 99.9% data availability over the course of the demonstration	Not Met – Total energy error was <10% only for certain low-variability loads.
Qualitative Objectives			

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[4] Evaluation of meter accuracy during laboratory testing demonstrated that comparison to stated accuracy in product literature was not appropriate for field testing success criteria. Accuracy values in product literature were developed using controlled voltage/current sources and are not reflective of in-field operation and therefore should not be the success criteria for this objective.

Ease of Installation and Integration with GSA Information Technology (IT)/Enterprise Systems	• Level of technical expertise required • Time required to install and configure • Customer labor associated with install • Data integration requirements • Security requirements • Ease of visualizing and downloading data	• Ability to be installed in the majority of GSA's electrical panels • Ability to integrate into GSA Link infrastructure • Generally applicable to >70% of GSA facilities	Met – Successfully and efficiently installed in a variety of panels. Demonstrated integration in software components of GSA Link.
Value Proposition and Cost-Effectiveness	• Installation and operations and maintenance (O&M) cost • Energy and cost savings identified • Value of tenant billing • Value of FDD	• Potential savings exceeds expected installation, O&M costs • Software offers measurement and analytics capabilities that address industry needs • Data from software can be utilized to identify a significant portion of the faults and ECMs identified by the GSA Link software (75% or more) • Determine if life cycle is cost-effective as a standalone platform	Met – Technology demonstrated ability to identify relevant behavior (e.g., cycling, on/off, seasonal trends)

B. TEST BED SITE

The location selected for this demonstration was the César E. Chávez Memorial Building in downtown Denver, Colorado. The site is a mid-rise office building of 10 stories with electrical risers and dedicated electrical rooms for each floor. It is a high-efficiency, all-electric, well operated building.

Figure 3: César E. Chávez Memorial Building (Credit: TRYBA Architects[5])

The CLASP technology was installed in four separate locations within the building: (1) the 7th floor electrical room, (2) the 6th floor electrical room, (3) the 9th floor electrical panels that serve the HVAC equipment for that floor and its server room, and (4) all HVAC equipment located in the penthouse (including two centrifugal chillers and two air handling units [AHU]). The revenue-grade submetering equipment was installed in the 480-V panel on the 7th floor to meter a variety of loads that the CLASP was monitoring in that panel. The NREL reference equipment metered lighting, HVAC, panel mains, and the transformer feeding the panel. This combination of circuit-level submetering allowed us to capture multiple load types in the building.

The following site selection criteria were established as relevant criteria for an effective test of the circuit-level submetering technology and were used in the selection of this site:

Required Characteristics

- Multi-tenant building
- The panels are 120/208 V or 277/480 V three-phase
- Modern identifiable commercial three-phase breaker panels with non-constant load
- Each circuit in the panel serves only one tenant/one end-use type
- Panels provide sufficient space for installation of CTs and provide space to install a voltage tap (e.g., via a spare breaker)
- Electrical room provides space for temporary installation of ancillary metering equipment for independent M&V

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[5] https://www.trybaarchitects.com/portfolio/cesar-e-chavez-memorial-building

  - Location of the electrical panels has good to excellent 4G wireless reception
  - The breaker panel circuits are well mapped (i.e., require no circuit tracing and have a current panel card)

Preferred Characteristics

  - One breaker panel will serve a data center
  - The breaker panel serves loads of mixed types (e.g., lighting and plug loads)
  - One breaker panel in the building is a main panel
  - The building is a small commercial building—the metered area of the building covers approximately 15,000 ft^2.

The demonstration site meets most of the recommended criteria, except that it is not a small building. Therefore, whole-building utility data were not able to be used for M&V, and one breaker panel was not the main panel for the building.

C. METHODOLOGY

QUANTITATIVE STUDY DESIGN

To establish the accuracy of circuit-level submetering, revenue-grade submetering was installed alongside the submetering technology under test, and data were pulled from the two systems at the same frequency. This enabled comparison of power readings from the two different systems over an extended period of time. In this section, we describe both the laboratory and field-testing configurations as well as the circuits studied and associated loads.

i. Laboratory Testing Design

For the laboratory testing, circuit-level submetering was installed in a residential panel within the Systems Performance Laboratory in the ESIF (see Figure 4). This panel has high-fidelity submetering of all the circuits permanently installed to assist with the research in the laboratory. This monitoring equipment was leveraged for the laboratory testing portion. The equipment consists of Ohio Semitronics PC5[6] watt transducers and metering class CTs. The 120-V circuits use the PC5, which are accurate to +/- 0.5% (including combined effects of power factor, repeatability, linearity, and current sensor). The 240-V circuits use PC5 meters connected to metering class CTs (accurate to 0.3%).

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[6] http://www.ohiosemitronics.com/media/specsheets/PC4_PC5.pdf

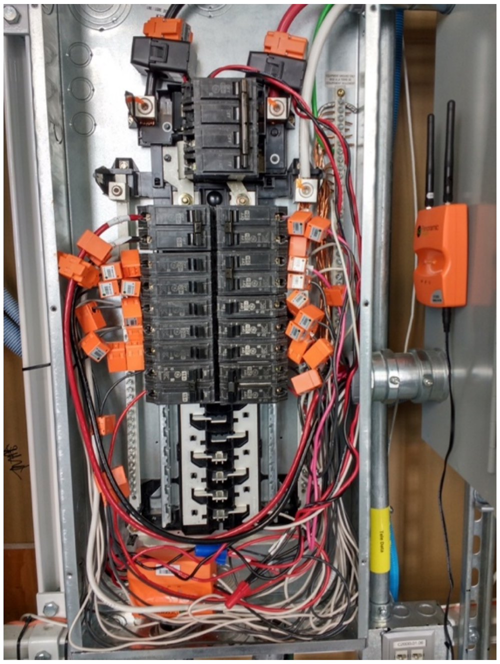

Figure 4: Electrical panel install for laboratory testing; CLASP technology shown (orange sensors) installed on circuits with an associated bridge mounted next to panel (Credit: Willy Bernal, NREL)

The CLASP technology under test was installed to monitor eight circuits within the electrical panel. Two PAN-12 were installed to monitor the range and the panel mains and to enable comparison between a “standard” configuration where a single CT is applied to capture multiple phases (assuming balanced phase draw) and a “split” configuration where you actually measure the current in each phase with a dedicated CT. The panel layout and the associated circuits under test are shown in Table 4. Each of the measured devices were cycled on for 1-hour periods, and power and energy data were collected from both the CLASP technology and the high-fidelity laboratory metering at 1-minute intervals over that period.

Table 4: Panel Schedule and Devices Monitored for Laboratory Testing

Measured	**Device**	**Capacity (A)**	**Circuit**			**Capacity (A)**	**Device**	**Measured**
PAN-12/ PAN-10	Range	50	**1**		**2**	30	Dryer	PAN-10
PAN-10			**3**		**4**			PAN-10
PAN-10	Refrigerator	20	**5**		**6**	30	Water Heater	PAN-10
	Dishwasher	20	**7**		**8**			PAN-10
	Garbage Disposal	20	**9**		**10**	20	N. Receptacles	
PAN-10	Washer	20	**11**		**12**	20	Countertop Receptacles	
PAN-10	Lighting	20	**13**		**14**	20	TV Receptacles	PAN-10
PAN-10	240-V Lighting Outlets	15	**15**		**16**	15	Instrumentation	
PAN-10			**17**		**18**			

ii. Field Testing Design

For the field demonstration, the circuit-level submetering technology was deployed to 13 separate panels and 4 circuit disconnects in the César E. Chávez Memorial Building. The disconnects corresponded to two chillers and two AHUs located in the penthouse (PH). Table 5 shows the type of load that was monitored for specific panels.

Table 5: Metered Panel Circuits

Floor	Panel	HVAC	Lighting	Servers/IT	Plug Loads	Panel Mains
6	PPD-6	30		3		
	LA-6	4				
7	PPD-7	24	6			3
	LD-7		1		2	3
	LDA-7				12	
	LD2-7	2		6	2	3
9	PPE-9	24	8			6
	L9-9 (Sect 1)	6				
	L9-9 (Sect 2)				8	3
	H9-9	9				3
	LE-9				7	3
	LEA-9	1				
PH	PPF-10	33				3
	Equipment (2 chillers and 2 AHUs)	4				

On each floor, a bridge (3G modem) was deployed to communicate the data from the CLASP to the cloud-hosted database for long-term data storage. The bridge communicates wirelessly with the CTs via a proprietary protocol. Data were transmitted on a 1-minute interval.

To assess the accuracy of the readings acquired by the circuit-level submetering, revenue-grade submetering was deployed alongside the CLASP in panel PPD-7. The revenue-grade submetering was deployed on eight separate loads in the PPD-7 panel, including four fan-powered, variable air volume (VAV) boxes, three lighting circuits, and the high side of the step-down transformer that fed all the low-voltage panels for the floor. We monitored each phase of the five three-phase circuits: four VAV boxes and one transformer. Each lighting circuit only required a single CT because they were single phase. Each

WattNode can monitor at most three phases. Thus, we required six WattNodes to monitor all the loads: five for each three-phase circuit and one for the three single-phase lighting circuit.

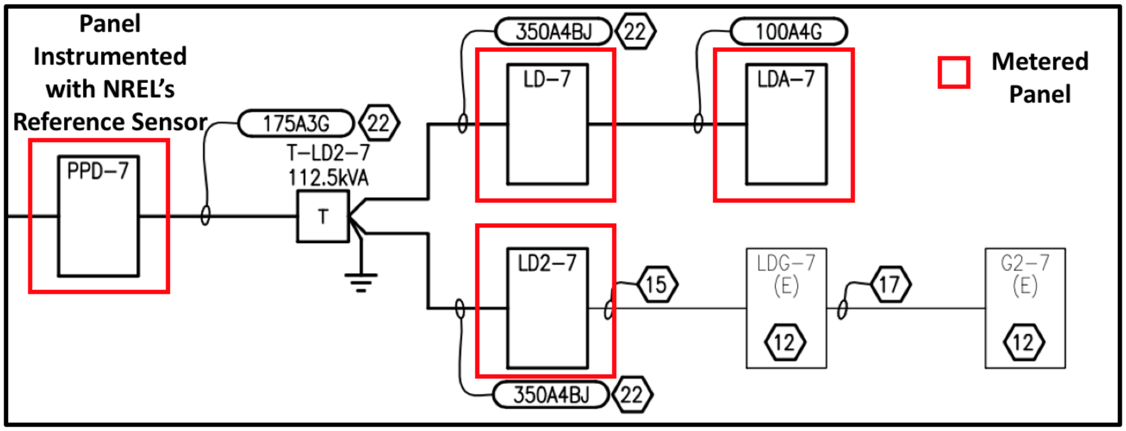

Figure 5: Metered panels on the 7th floor

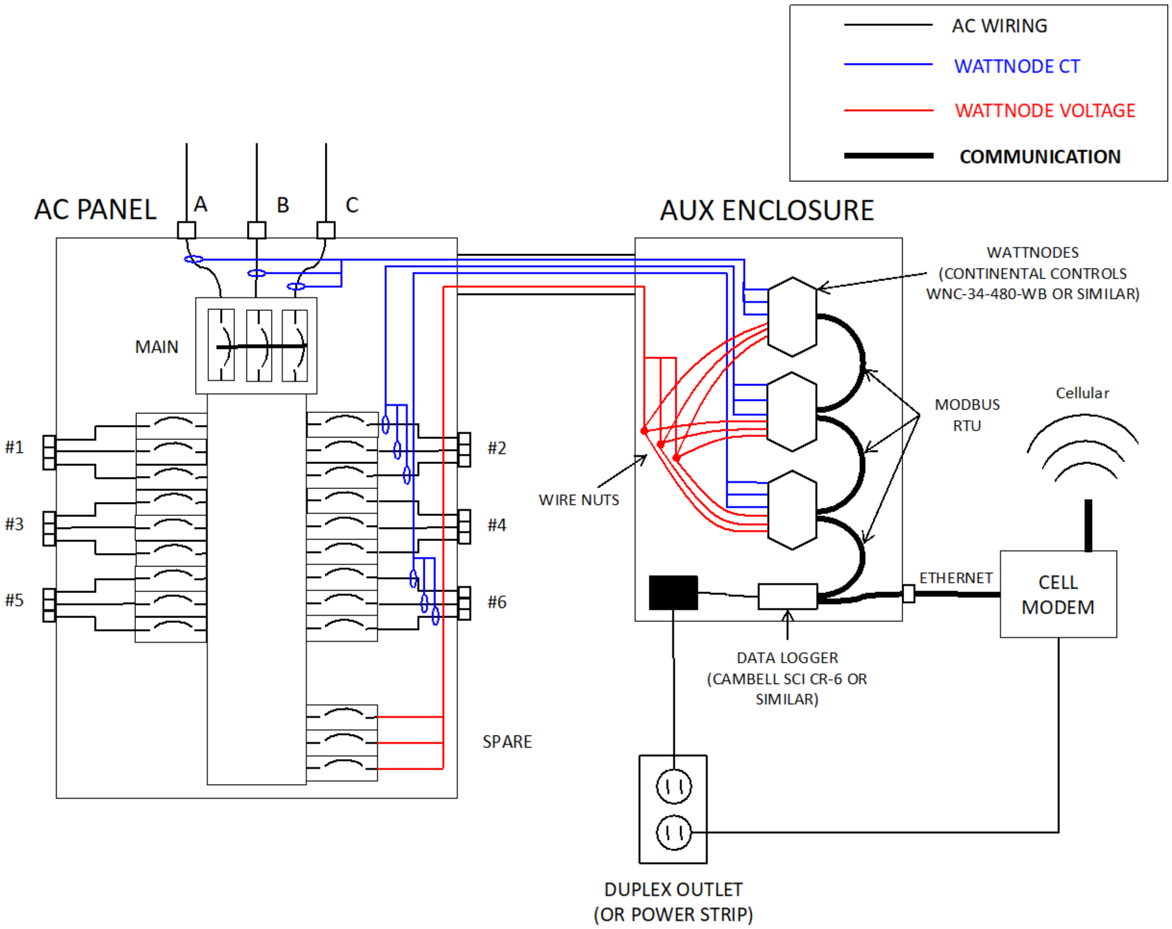

Figure 6: Diagram of NREL submetering configuration (only three WattNodes shown for clarity, six utilized in field demonstration)

The revenue-grade metering technology that was used to assess the accuracy consisted of Continental Control's WattNode Revenue (RWNC-3Y-480-MB) combined with Continental Control's revenue-grade Accu-CTs. The Accu-CTs provide accuracy of 0.5% and are tested to ANSI C57.13, Class 0.6 in conjunction with the associated WattNode to ensure ANSI C12.1 accuracy (0.5% accuracy). The WattNodes are connected to a Campbell Scientific CR-6 data logger via MODBUS communications, and data are communicated from that data logger out to a cloud-hosted database via cellular communications. Data were collected at 1-minute intervals from the Campbell Scientific data logger. A typical configuration is shown in Figure 6.

Final install for the 7th floor electrical panel (PPD-7) with the CLASP technology and six Continental Control's meters are shown in Figure 7.

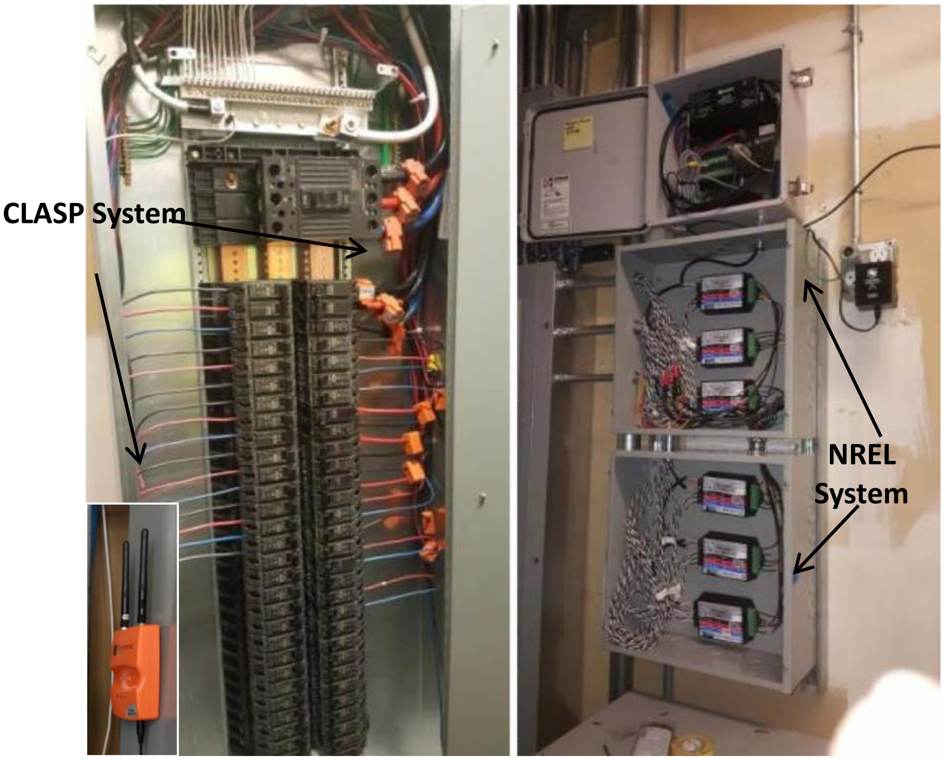

Figure 7: CLASP's CTs and bridge (left) and Continental Control equipment (right) (Credit: Willy Bernal, NREL)

QUALITATIVE STUDY DESIGN

To assess the ease of installation for the circuit-level submetering system, NREL observed the electrician's process for installation during the single-day install. Informal interviews were carried out with the electricians after installation was complete.

To assess the ability to integrate effectively into the enterprise analytics platform GSA Link, NREL worked with GSA Link administrators to find potential pathways for data integration. Additionally, NREL reviewed the set of standard FDD rules that are deployed as part of the base GSA Link deployment during a new install. This review provided a qualitative assessment of what categories of rules the circuit-level submetering data would be able to assist in addressing, what categories of rules they would enable, and what categories of rules they would not be able to address sufficiently.

DATA ANALYSIS

Data from the circuit-level submetering system were pulled via the vendor's API on a 1-minute interval. Similarly, the data from the revenue-grade submetering were pulled from the LoggerNet website in 1-minute intervals. These data were aligned on timestamp, such that the value at each timestep could be compared between systems.

To calculate the accuracy of the power and energy readings from the circuit-level submetering system, bias and normalized bias (or percent error) were calculated for every timestep during the observation period. The bias in between the two readings is defined as: $x_{\text{meas}} - x_{\text{obs}}$, where x_{meas} is the CLASP's measurement and x_{obs} is the revenue-grade submetering. Percent error is defined as $(x_{\text{meas}} - x_{\text{obs}})/x_{\text{obs}}$. Both the bias and the percent error were then averaged over all timesteps and reported as the mean bias and the average percent error. These values show whether the measurements were consistently high or low on an absolute and percent basis, respectively.

These errors were then summarized into a root mean squared percent error (RMSPE) to quantify the magnitude of the combined error in the measurements. RMSPE is defined as:

$$\text{RMSPE} = \sqrt{\frac{\sum_{i=1}^{n}\left(\frac{x_{\text{meas}} - x_{\text{obs}}}{x_{\text{obs}}}\right)^2}{n}}$$

It was critical to use the root mean squared *percent* error instead of simply the root mean squared error because of the variability in some of the loads. For highly variable loads, larger absolute errors can occur at higher loads where the actual percent error is exactly the same as at a lower load point. This fact skews the root mean squared error metric (as well as standard deviations), despite the fact that their accuracy on a percent basis is consistent across the measurements. Therefore, all errors were reported on a percent basis with respect to the reference measurements.

To assess the total uncertainty of the CLASP's measurements, it is necessary to account for the uncertainty of the reference sensor (provided by the manufacturer). The total uncertainty should consider the uncertainty of the reference sensor and the estimated uncertainty of the CLASP system with respect to the reference sensors:

$$Total\ Uncertainty_{\text{CLES}} = \sqrt{(Uncertainty_{\text{CLES/REF}})^2 + (Uncertainty_{\text{REF}})^2}$$

III. Demonstration Results

This section describes the quantitative and qualitative results for both stages of the project: the laboratory testing and the field deployment. Section III.A presents the results for accuracy testing both in the laboratory and in the field. Section III.B presents the results for the qualitative objectives of ease of installation and ease of integration into GSA Link.

A. QUANTITATIVE RESULTS

LABORATORY ENVIRONMENT

i. Objective 1 (Quantitative): Submeter Accuracy in Laboratory Environment

As described in Section II.C, circuit-level submetering was deployed on a single residential panel in the Systems Performance Laboratory in NREL's ESIF, and accuracy was assessed via a set of controlled 1-hour tests for each of the different appliances (as well as certain combinations of appliances). The readings from the CLASP were compared with the high accuracy power monitoring equipment in the laboratory. The raw data from the CLASP and the laboratory power monitoring equipment were pulled at 1-minute intervals. These data were also aggregated to 15-minute data, and accuracy results were calculated at this coarser time resolution. The 15-minute aggregation was performed because the applications outlined for this study (e.g., fault detection) generally do not require finer resolution than 15-minute data.

An additional note on data acquisition by this CLASP system is that the CTs are self-powered by the current going through the wires they are metering. This enables the CTs to be completely wireless and not require batteries nor external power supply (an extremely beneficial characteristic for deployment and maintenance). However, this wireless feature does constrain the sensors to only work when there is sufficient current passing through the wire (approximately 0.75–1 A). This factor limits the system to only record currents above 0.75–1 A (90–120 W for 120 V), with no data reported for periods where the device is consuming less than 1 A. This impacted the ability to record data for certain devices (or periods of device cycling) in both laboratory and field testing. In all cases, the error calculations presented in this report were performed only for periods where the CLASP were recording data (i.e., no accuracy penalty for lack of data during low amperage periods).

The results show that the CLASP was able to capture the dynamics and magnitude of the loads during the laboratory testing, such as the clothes dryer and electric range. Figure 8 shows time series data for the testing of these two pieces of equipment. The "CLASP (Std.)" data in the figure correspond to a standard deployment approach for the CLASP system. In a standard install, a single CT is deployed on loads with multiple phases, and readings are multiplied by the number of phases present (in this case multiplied by two for split phase loads such as a dryer). Therefore, with unbalanced loads, this can lead to error in the total power calculation. Additionally, these readings use a reference voltage that is input by the user, either based on spot check of the panel voltage or based on the rated voltage for the panel.

The "CLASP (Split)" data in Figure 8 show measurements that used separate sensors on each leg of split phase loads, improving accuracy of the measurements. These data also utilized voltage readings from a PAN-42 installed in the panel, correcting for actual voltage at every measurement. The CLASP deployment application is capable of selecting either a static voltage reading or an installed PAN-42 sensor to accomplish voltage correction; the PAN-42 option was utilized to improve data accuracy in the "CLASP (Split)" data. The "reference" label in the figure corresponds to the laboratory metering data.

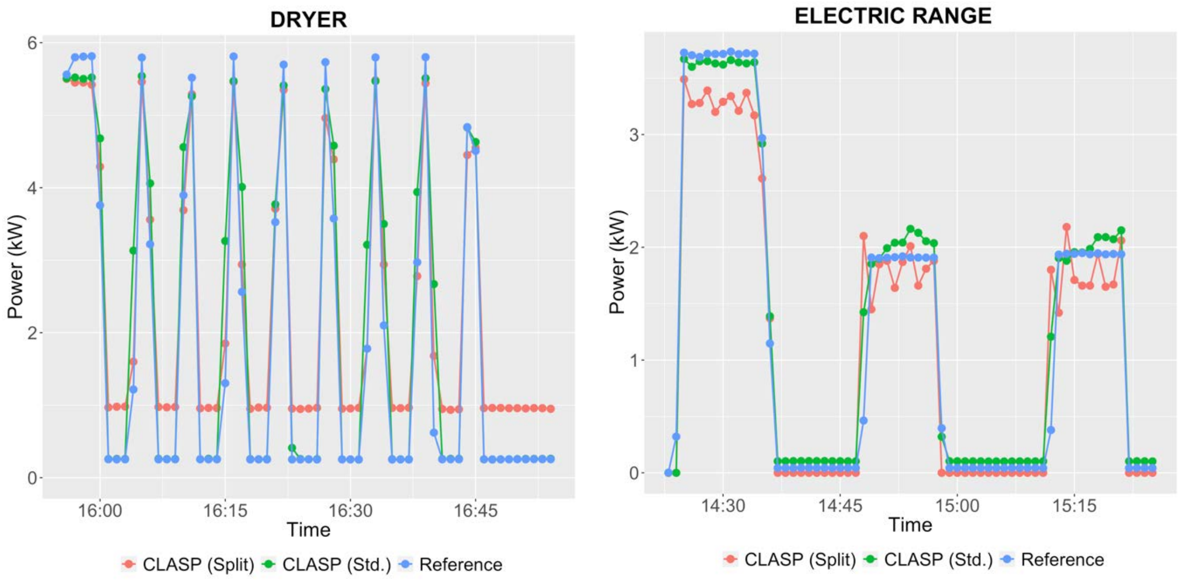

Figure 8: Vendor measurements vs. reference readings

The quantitative results are presented for each of the eight 1-hour tests in Table 4 (accuracy results comparing the 15-minute data). These data are for the split phase measurements, and voltage measurements from the PAN-42 are used in calculating the power values. The error for total energy is below or around 10% for some appliances: refrigerator, dishwasher, lighting, water heater, TV/DVD, and range. Most of them feature steady power profiles and power factors close to 1. Other loads present much higher total energy errors (e.g., 95% for the washer) due to the lower power factors and cycling behavior.

Table 6: Empirical CLASP Sensor Uncertainty for "Split" Configuration (15-Minute Data)

Trial	Appliance	Voltage (V)	Mean Power (W)	Mean Bias (W)	Average Percent Error (%)	RMSPE (%)	Total Energy Error (%)
1	Refrigerator	120	143.76	4.81	8.93	39.46	10.52
2	Dishwasher	120	400.58	28.4	5.54	6.22	4.92
3	Washer	120	130.3	118.61	103	105.31	95.3
4	Lighting (All)	120	539.6	29.78	4.77	4.79	4.78
5	Lighting (240 V)	240	115.05	-37.37	-31.82	31.96	-31.76
6	Dryer	240	2,204.98	330.46	31.09	39.28	22.39
7	Water Heater	240	1,777.81	-172.47	1.7	13.81	-8.08
8	TV/DVD	120	105.9	-11.34	-12.33	12.39	-12.32
9	Electric Range	240	1,309.15	-90.45	-4.73	8.1	-7.2

The results of the laboratory testing did not meet the performance objective of achieving <+/-2% error for both energy and power during testing.

SITE DEPLOYMENT

i. Objective 2 (Quantitative): Submeter Accuracy in Field Deployment

After laboratory testing, the CLASP was installed in the César E. Chávez Memorial Building in Denver, Colorado. Accuracy analysis was performed on a variety of loads in the main panel of the 7th floor (480-V panel, PPD-7). Loads that were monitored with both the CLASP and the high-accuracy NREL submetering system included multiple fan-powered VAVs, multiple lighting circuits, and the transformer feeding the remaining low-voltage panels on the 7th floor.

For the field deployment, the CLASP was deployed in standard approach for the vendor. This meant that we installed a single CT on most three-phase equipment, such as the fan-powered VAVs (meter mains received a single CT per phase), and that power data were calculated assuming a power factor of 0.95 and voltage of 485 V (based on spot check) for all sensors without a voltage tap. After installation of the metering system, we noted that the power calculations for the VAVs differed significantly between the CLASP measurements and the NREL submetering system. This was due to a significant imbalance among the three phases, with the fan powered by one phase and the electric reheat powered by the other two. While this highlights a potential issue associated with the standard deployment approach for this CLASP, we did not want to unduly penalize the accuracy calculations of the system due to this phase imbalance. Therefore, for the fan-powered VAV measurements, all results (figures and tabular data) only present measurements for phase A power (this is the actual phase A measurement from the NREL submetering system and the CLASP measurements divided by three). It was confirmed that the CLASP CTs were on phase A of the devices, and dividing by 3 would undo the internal calculation made by the CLASP system to provide the actual calculated phase A power.

Similar to the laboratory testing, results show that the CLASP captured the trend of the load profile quite well, even for high-variability loads. Figure 9 shows one day of measured data for a representative lighting circuit and a week of measured data for a fan-powered VAV box, comparing reference data to CLASP data. The lighting load represents a load that does not cycle significantly and has a power factor close to the assumed value of 0.95. Thus, the CLASP readings agree closely with the reference. However, the VAV system has worse accuracy due to the large power swings and a constant offset during periods when the system is on. Additionally, there is a portion of the time with the VAV system where the CLASP does not record readings due to a low amount of current running through the wire. This is shown as zero in the figure; however, as stated previously, it does not factor into the accuracy calculations.

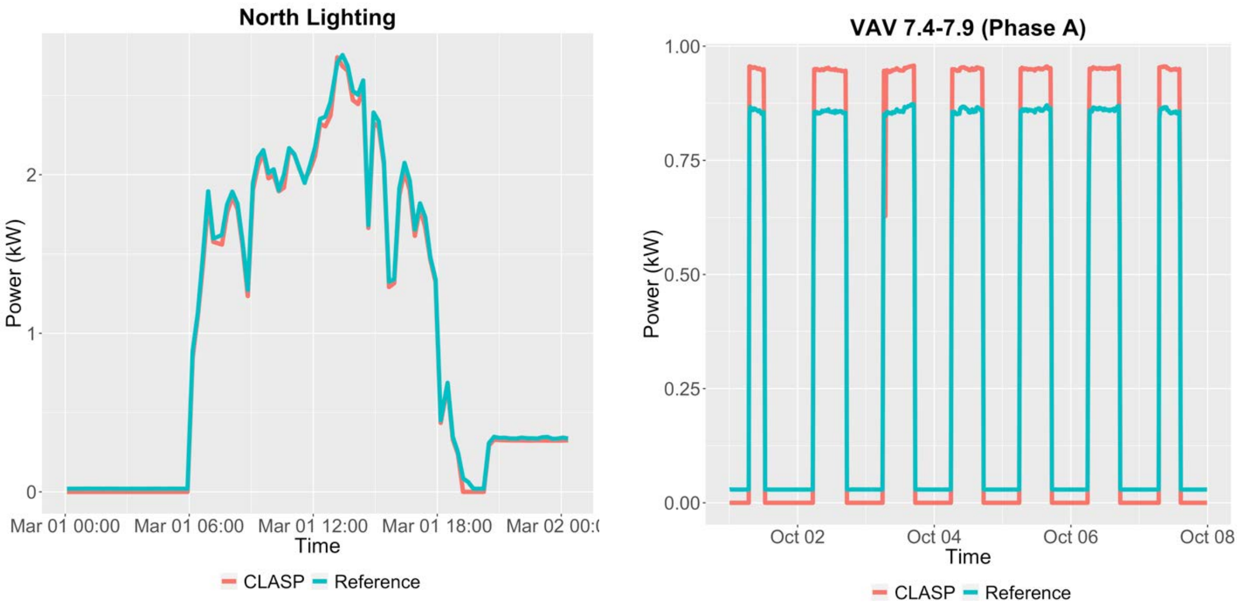

Figure 9: Representative time series data comparing CLASP measured data (CLASP) with NREL submetering (Reference)

The calculated power measurement accuracy of the CLASP during the field deployment was not consistently under 10%. For steady loads like lighting, RSMPE was low (~5%). However, for more irregular loads, the error was greater (e.g., RSMPE of 9%–33% for VAVs). Table 7 shows the uncertainty during the month of November 2017. During this month, the total energy error was found to be below 10% for all loads except the VAV 7.2. This unit sustained considerably more cycling than the other VAVs. The RMSPE was only under 10% for the more consistent loads: lighting and the transformer. The CLASP produced larger errors for all VAVs because they presented the most significant cycling.

Table 7: Data Statistics for November 2017

Trial	Equipment	Voltage (V)	Average Power (W)	Mean Bias (W)	Std. Dev. (W)	Average Percent Error (%)	RMSPE (%)	Total Energy Error (%)
1	VAV 7.1 (Phase A)	480	120.4	0.9	78.5	31.6	39.4	0.7
2	VAV 7.2 (Phase A)	480	648.6	164.3	178.1	34.5	60.8	25.3
3	VAV 7.3 (Phase A)	480	437.0	13.1	79.1	16.5	26.3	3.0
4	VAV 7.4–7.9 (Phase A)	480	354.4	18.0	61.3	10.8	12.4	5.1
5	Lobby Lighting	480	152.8	-11.8	9.2	-1.3	5.1	-7.7
6	North Lighting	480	671.7	-2.7	32.6	0.7	4.4	-0.4
7	West Lighting	480	778.6	-73.2	26.9	-3.5	4.8	-9.4
8	Transformer LD7-2	480	9,391.3	682.8	292.2	7.6	8.4	7.3

Table 8 shows total energy error for 15 months during the deployment. The energy error for the lighting loads and the transformer do not change significantly at different seasons because they sustain very similar power profiles and characteristics. On the other hand, the error changes considerably for the VAVs according to the month; this is likely due to limited use during the shoulder and summer months, leading to fewer measurements (and many of those measurements during on/off cycles) because the system only records above a threshold current. Whenever the current measurements were below a certain level, the CLASP technology would record zero Watts (or Amps). The wireless CTs are self-powered and required a minimum amount of current to turn on and record data. Thus, the CLASP could not record low readings below the 0.5–1 A range. There are many monthly energy error values <10%, but there are also higher values spread across both devices and seasons (with maximum absolute error of 52%).

As previously noted, this CLASP system has two possible configurations: one requiring a voltage tap plus CTs and one that only requires CTs. As the latter configuration did not meet the accuracy requirements laid out in the performance objectives, the voltage tap configuration was also deployed and its accuracy assessed. This device was installed to measure the high side of the stepdown transformer, and 3 months of measurement data were collected. Figure 11 compares the power consumption readings for the three-phase transformer during a single day, showing the NREL reference data, the standard (no voltage tap) CLASP data, and the CLASP deployed with a voltage tap. Accuracy was slightly improved during the 3 months that the setup with voltage tap was deployed. However, the improvement was very limited, with the total energy error decreasing from 7.16% to 7.03% over the 3 months. The total energy values for both configurations are also shown in Table 8.

Table 8: Total Energy Error

Equipment	2016			2017											
	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
VAV 7.1 (Phase A)	-36.32	6.67	2.43	3.48	3.55	4.64	2.18	7.07	NA	NA	NA	-23.16	3.32	0.67	8.36
VAV 7.2 (Phase A)	38.11	18.94	7.09	-2.79	14.75	14.48	11.5	37.8	NA	NA	NA	6.94	22.13	25.33	23.25
VAV 7.3 (Phase A)	-5.74	2.5	0.58	-0.27	-2.59	-3.15	-8.19	-14.52	NA	NA	NA	-13.71	1.73	3	3.12
VAV 7.4–7.9 (Phase A)	2.26	4.05	1.83	-2.71	2.1	0.99	-0.64	-8.02	NA	NA	NA	-7.11	4.8	5.06	10.61
Lobby Lighting	-8.73	-8.07	-13.88	-15.16	-9.83	-9.36	-12.82	-8.94	-7.16	-21.69	-7.66	-8.73	-7.51	-7.7	-7.26
North Lighting	-2.59	-0.56	-7.14	-6.63	-4.09	-3.2	-4.17	-2.69	-0.7	-12.06	-0.59	-1.25	-0.07	-0.4	-0.22
West Lighting	-4.99	-4.48	-30.06	-52.47	-7.83	-8.43	-28.31	-16.32	-8.1	-21.21	-8.25	-9.74	-9.29	-9.4	-7.9
Transformer (PAN-14)	5.01	4.88	-8.95	-27.54	1.62	1.78	3.47	4.61	6.01	5.27	5.65	7.07	7.07	7.27	7.13
Transformer (PAN-42)													7.06	7.21	6.83

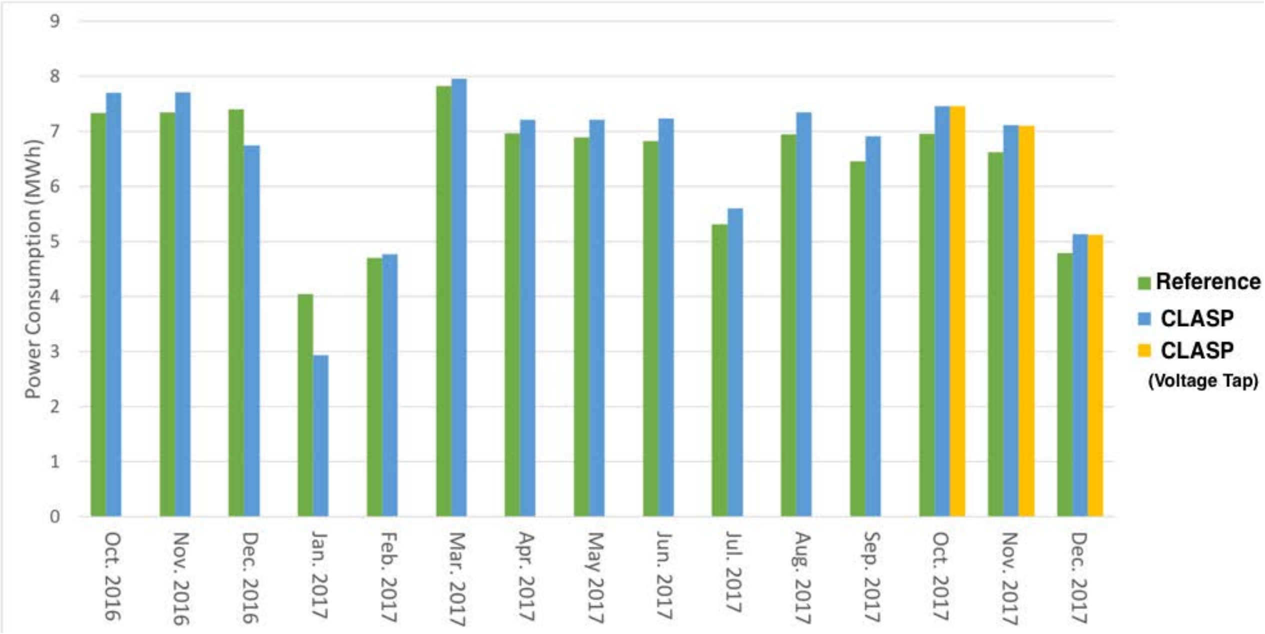

Figure 10: Transformer energy consumption

In summary, we observed similar accuracy limitations during the field deployment as in the laboratory setting. Sensors tracked the lighting loads the best. The RMSPE was consistently under 6% for the lobby, north, and west lighting. The system was able to capture correctly large power loads such as the transformer. The RMSPE for the three-phase transformer was consistently less than 10% (8.39% for November 2016). Yet, the performance objective was not met for all devices.

We also estimated the accuracy of the current readings with respect to the reference metering equipment. This eliminates the impact of the voltage and power factor assumptions from the accuracy assessment and more directly assesses CT accuracy (though the actual power values are what is of interest for GSA use cases). The following figures show current comparison for the north lighting and phase A of the VAV 7.4 and 7.9. The average percent error (%) and RMSPE (%) are very similar to the ones produced from the power measurements. Table 9 summarizes the accuracy results by analyzing the current data for the month of November 2017. During calculations, we removed all readings where the CLASP's CT did not exceed the operating threshold to function properly (<0.5 A). This operating threshold was discussed previously in this section.

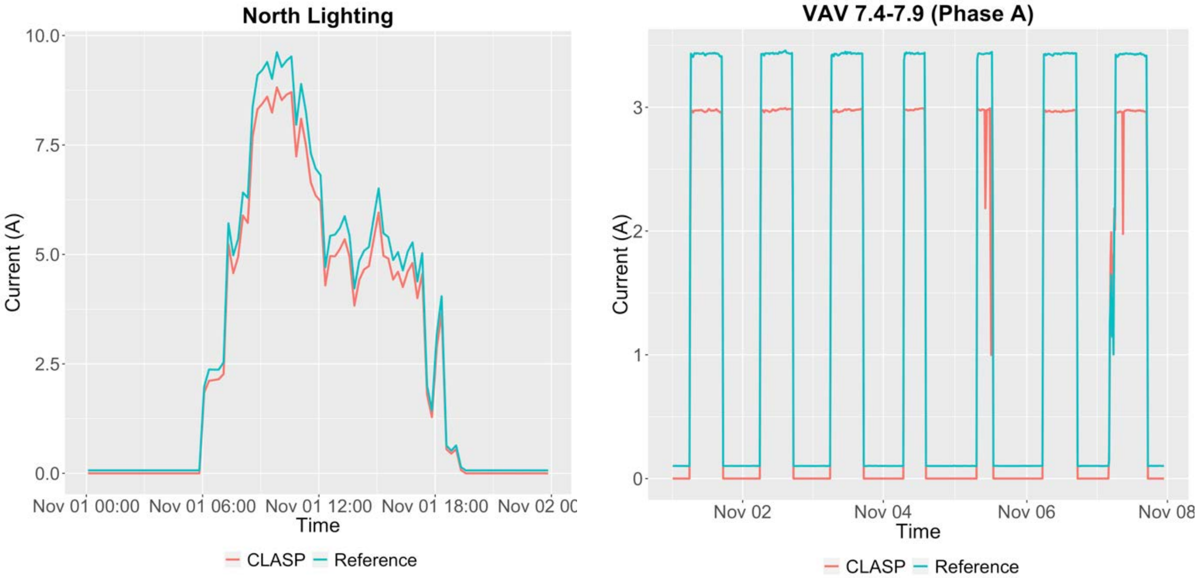

Figure 11: Time series data comparing current readings from the CLASP measurements (CLASP) versus the NREL submetering (Reference)

Table 9: Data Statistics for the Current Readings for November 2017

Trial	Equipment	Voltage (V)	Average Current (A)	Mean Bias (A)	Std. Dev. (A)	Average Percent Error (%)	RMSPE (%)
1	VAV 7.1 (Phase A)	480	0.5	0.4	-0.1	8.0	25.8
2	VAV 7.2 (Phase A)	480	2.3	2.6	0.3	19.9	48.4
3	VAV 7.3 (Phase A)	480	1.6	1.4	-0.1	3.0	18.8
4	VAV 7.4–7.9 (Phase A)	480	1.4	1.2	-0.2	-13.0	13.9
5	Lobby Lighting	480	0.6	0.4	-0.2	-13.8	15.9
6	North Lighting	480	2.4	2.1	-0.3	-9.8	10.5
7	West Lighting	480	2.8	2.2	-0.5	-14.4	14.6
8	Transformer LD7-2	480	27.6	31.6	4.0	14.7	15.8

B. QUALITATIVE RESULTS

i. Qualitative Objective 1: Ease of Installation and Integration with GSA Link System

a. Installation Summary

The CLASP technology evaluated in this report makes it easier to meter individual loads in a panel due to small form factor components (e.g., CTs and bridge), wireless CTs and bridge, plug and play CT design, and pre-configured cloud-hosted data storage. The CLASP technology features an innovative approach for metering loads: wireless split-core CTs without the need for voltage taps. It also provides a product for more traditional CLASP metering, where voltage taps are required to attain higher accuracy readings. The technology is applicable for any standard electrical panel and can also be used to monitor large device disconnects.

Installation of the wireless CTs necessitates opening the electrical panel cover and, therefore, requires a licensed electrician for the install (in accordance with applicable safety and contracting requirements). The CTs are powered through a current going through the wires to which they are attached to and, therefore, do not require cabling and are easily installed. During the installation for this technology demonstration, the entire installation was able to be performed without de-energizing the panel.

Once the CTs are installed, a simple process is required to associate the unique identifier (UID) associated with each individual sensor to its location within the electrical panel. This creates a mapping from the individual sensor to the specific load/phase that it is metering, assigns it to a type of load, and builds up the hierarchy and associated metadata that the web interface uses to provide insight, analytics, and rules/alarms.

To transport the data from the CLASP bridge to the cloud-hosted data storage, one can use the built-in Ethernet jack, Wi-Fi, or cellular (3G GSM) communications. There is a SIM card slot in the CLASP bridge, and this can be used to connect to optional cellular connections. Due to the pilot nature of this technology demonstration, it was desirable to use cellular communication and avoid connecting to the building ethernet. This was primarily due to project timeline considerations because there was a lengthy cyber review and approval process for connecting a new device to the LAN. The initial cyber review did not flag any concerns with the device and allowed installation for the pilot project with cellular communications.

The installation of CLASP for the César E. Chávez Memorial Building comprised of 5 separate CLASP bridges that collected data from 144 individual CTs distributed in 13 panels and 4 HVAC equipment disconnects. The installation took place in one day and required two electricians working approximately 4 hours each, with support from NREL personnel for double checking the installation and commissioning. There were no significant challenges with the installation because there was no need for mounting electrical boxes or running conduit from the electrical panels. As noted above, this installation used 3G cellular to transport the data from the bridge to the cloud using the built-in cellular capabilities and antenna provided by the CLASP bridge. The 3G cellular approach enabled a streamlined pilot project timeline and required minimal additional labor hours. However, a monthly cell subscription was needed for data transmission during the length of deployment. This may not be required when ethernet drops are available for the meters to connect directly into. While no official interviews were conducted during the installation of this CLASP product, the installing electricians noted that the product installation was extremely simple and fast and were surprised because they had never encountered a similar technology.

They also indicated that the deployment tool was very useful for debugging errors and problems that arose. CLASP's deployment tool is a software program designed to streamline the installation of meters. The tool allows: (1) hierarchically organizing relationships between buildings, floors, zones, panels, and loads, and (2) debugging any errors that occurred during the installation by quickly visualizing the readings for recently installed sensors.

As soon as the CTs were clipped onto the wires and configured into the deployment tool, we could monitor their readings using the deployment software that provided local communication with the bridge for debugging purposes. After the installation, streaming data were readily available via the web-based user interface or the API. All of this occurred within the one-day install.

The CLASP technology has been designed and is advertised as a standalone system for data analytics and reporting. However, the technology can be integrated with GSA Link, a system that connects the building management system to a central cloud-based platform using SkySpark.[7] During the accuracy verification analysis, NREL pulled data through the CLASP API and uploaded it to an NREL SkySpark server for data storage, processing, and analysis. This demonstrates that a similar approach is viable to work with the GSA Link system. The only significant challenge is expected to be ensuring firewall exception requests to be able to access the web-hosted data storage via the supplied API.

This CLASP also offers a data analytics platform that can be leveraged directly without the need to use the GSA Link platform. This can provide energy savings strategies, fault diagnostics, and data visualization (e.g., charts and trends) for buildings without a BAS.

C. COST-EFFECTIVENESS

i. Qualitative Objective 2: Value Proposition and Cost-Effectiveness Analysis

This objective is challenging to assess for CLASP technology because the technology provides data that can drive energy savings but does not actually save any energy directly. Additionally—as discussed in Section I.B—there are various use cases that CLASP can support, each with their own potential revenue streams. Finally, many of these value streams are site-specific. For example, the FDD use case may have very different energy and cost savings potential in a building that has recently received retro-commissioning and is well managed versus a building that has been drifting out of tune for a number of years and has limited staff to support operations.

While it is difficult to establish general cost-effectiveness of this technology (for the reasons listed above), we provide two approaches to quantifying cost-effectiveness of CLASP in the context of this demonstration deployment at the César E. Chávez Memorial Building in Denver. The two approaches consist of:

1. Calculating the energy savings required to pay for a typical installation at the César E. Chávez Memorial Building (10-year analysis with 3% discount rate)
2. Quantifying the cost savings derived from a single identified ECM of turning one chiller off for winter months (December through March).

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[7] Skyspark is a platform for storing, visualizing, and analyzing building information data. https://skyfoundry.com/

a. Cost-Effectiveness: Calculating Required Savings

To establish the savings required to deliver a positive net present value, we calculated the capital costs and recurring fees throughout 10 years for a standard deployment for the whole César E. Chávez Memorial Building. This deployment would cover all 10 floors, with a focus on high-energy loads and panel mains. We present a 10-year analysis with 3% discount rate. The required savings for this scale of deployment would need to be greater than $2,840/year to result in a positive net present value for the building. This amounts to 1.3% of the building's total annual electricity costs of approximately $226,000. This is a relatively small percent savings, and it is considered likely that effective utilization of this system could result in greater than 1.3% costs savings. This analysis considers demand as well as volumetric charges. The blended electricity rate for the site is approximately $0.11/kWh. The volumetric energy rate is $0.0305/kWh while the demand charges are $19.19/kW and $23.45/kW for winter and summer, respectively.

The CLASP system for a typical installation in a 180,000 ft^2 building like the César E. Chávez Memorial Building would require 105 CTs, 10 bridges, and 10 voltage-tap-style meters (meters with voltage taps would be applied to panel mains on each floor). Annual fees for the CLASP are also included for all meters considered in a typical installation. All system costs, savings, and associated economic metrics are shown in Table 10.

Table 10: Economic Assessment—Energy Savings Required for Positive Net Present Value

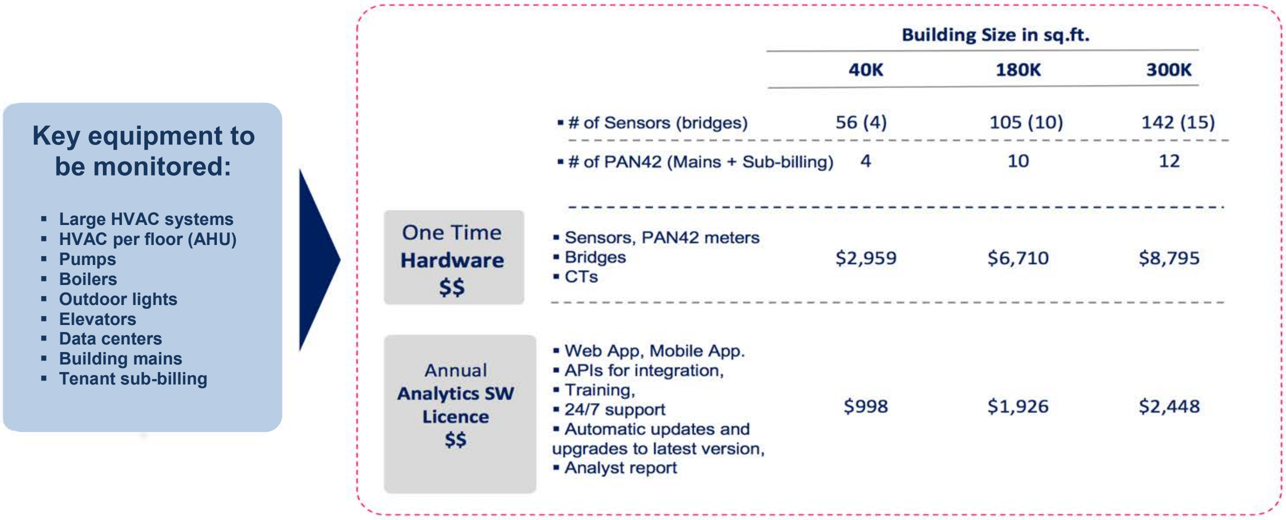
	Baseline (Before)	CLASP Technology (After)	Difference
Equipment Cost[1]	$0	$6,710	$6,710
Installation[2]	$0	$1,325	$1,325
Total Installed Cost Per Meter	$0	$63.9/meter	$63.9/meter
Annual Fees (Per Site)	$0	$1,926/yr	$1,926/yr
Annual Energy Costs (@ $0.0305/kWh[4])	$226,657/yr	$223,740/yr	$2,917/yr
Simple Payback	3.5 years		
Savings-to-Investment Ratio	1.0		
Net Present Value[3]	$0		

Required Percentage of Energy Cost Reduction	1.29%	

[1] Equipment lifespan is assumed to be 10 years.
[2] Labor is 21.5 hours at $52.50/hr.
[3] Assuming a 3% discount rate and a 0.15% electricity cost escalation rate.
[4] Energy costs from utility tariff structure.

We note that a simple payback period may not be the best metric for evaluating this technology given the relatively high recurring cost, which is not captured by this metric. This causes the payback period to look short even when the net present value of the investment is zero.

Figure 12 presents approximate technology costs for typical deployments in buildings of varying sizes. Note that we are not presenting the cost of deploying the 144 sensors installed at the César E. Chávez Memorial Building for this case study deployment but rather the cost of a typical installation with relevant loads for identifying ECMs and performing FDD. The reduced number of sensors identified here (and recommended by the vendor) is due to a reduction of plug load and lighting circuits—as compared to the demonstration install—and a focus on high load circuits and panel mains.



Key equipment to be monitored:

- Large HVAC systems
- HVAC per floor (AHU)
- Pumps
- Boilers
- Outdoor lights
- Elevators
- Data centers
- Building mains
- Tenant sub-billing

		Building Size in sq.ft.		
		40K	**180K**	**300K**
	▪ # of Sensors (bridges)	56 (4)	105 (10)	142 (15)
	▪ # of PAN42 (Mains + Sub-billing)	4	10	12
One Time **Hardware $$**	▪ Sensors, PAN42 meters ▪ Bridges ▪ CTs	$2,959	$6,710	$8,795
Annual **Analytics SW Licence $$**	▪ Web App, Mobile App. ▪ APIs for integration, ▪ Training, ▪ 24/7 support ▪ Automatic updates and upgrades to latest version, ▪ Analyst report	$998	$1,926	$2,448

Figure 12: Cost estimates for buildings (per the technology vendor)

b. Cost-Effectiveness: Derived from a Single ECM Identification

The CLASP vendor produced quarterly reports for the César E. Chavez Memorial Building summarizing energy consumption patterns, identifying potentially inefficient device operation, and identifying opportunities to reduce energy consumption. These findings were presented to the GSA building manager and the operations team to identify opportunities for implementing measures for operational savings.

Among the identified ECMs was the opportunity to turn off a single chiller during the winter months (December to March). The CLASP system identified that both of the central chillers were on at standby levels during the entire winter period, with each chiller consuming approximately 15 kW per day. It was recommended that the building consider shutting down one of the chillers (possibly alternating the chillers bi-weekly to achieve equal duty cycle) because this would provide online chiller capacity in case of warm periods during the winter months while also providing energy and cost savings for the building. Figure 13 shows the standby power consumption for both chillers during the month of December.

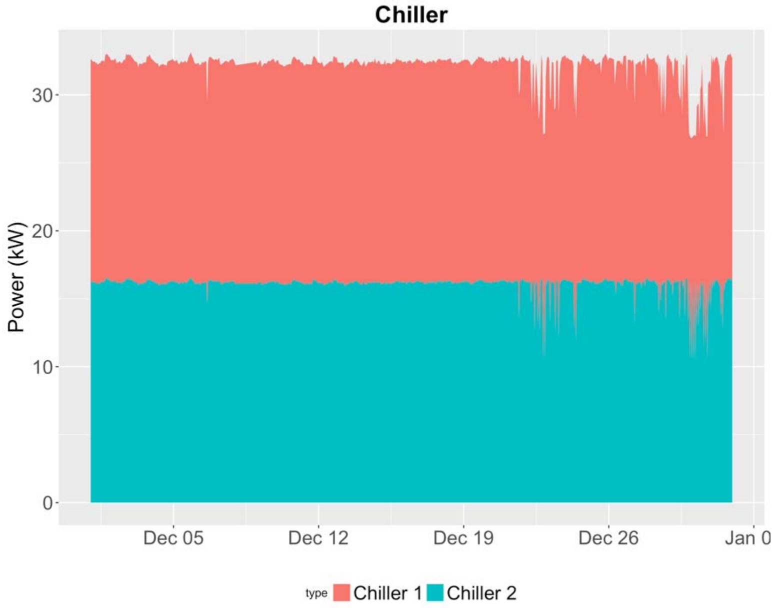
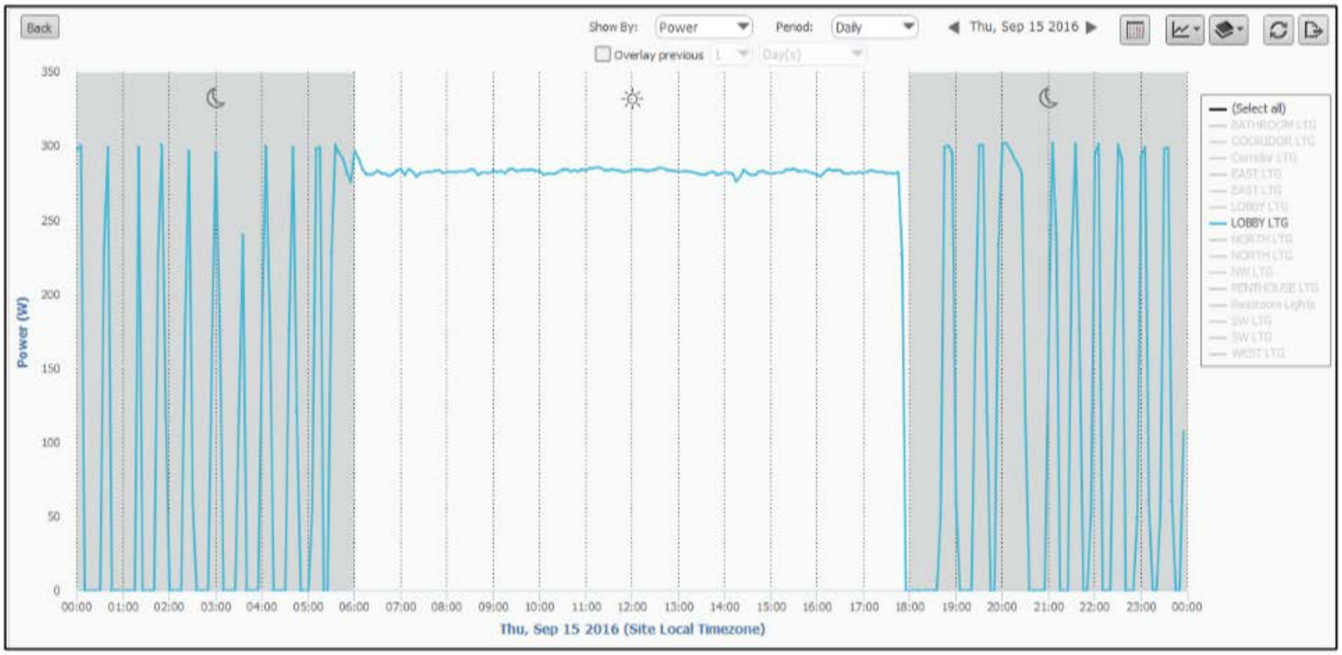


Figure 13: Chiller power consumption for non-cooling month (December 2016)

NREL analyzed this ECM opportunity to provide an example estimate of cost/energy savings that could be driven by this CLASP technology. Assumptions are that the building is able to shut down one of its two central chillers for the winter season, saving 15 kW consistently over that 4-month period. The 15-kW reduction was calculated using the actual CLASP data for that period, averaged from December 2016 to March 2017. Our calculations show that the building could save $2,482 per year, including $287 of demand charge savings and $333 energy savings per month throughout the 4 winter months. Even though this does not meet the 1.29% annual energy cost reduction that would deliver a positive net present value, we present this example to put into perspective the energy savings that the technology can potentially identify.

The ECM analyzed here is but one of various energy savings opportunities identified by the system during the first 4–6 months the CLASP technology was installed. The report provided by the vendor contained other insights about the equipment operation and identified opportunities for reducing energy consumption. The report includes highlights on equipment behavior that should be addressed (e.g., cycling of lighting loads at off-hours) to improve operational efficiency (e.g., identifying which chiller operates more efficiently at higher loads). In Figure 14 and Figure 15, we present two examples of the ECMs identified in the vendor's quarterly reports.



Show By: Power

Period: Daily

☐ Overlay previous 1 Day(s)

Thu, Sep 15 2016

Figure 14: Off-hours cycling of lobby lighting

Figure 14 shows unusual behavior from the lobby lighting load: the load cycles approximately every 30 minutes during off-hours. This would require further observation and discussion with the building manager to identify if this is the intended operation behavior (could be janitorial staff during nighttime hours). Figure 15 presents the “Dual AC” load short-cycling throughout the day and night. This might not be the intended behavior, and further inspection is warranted. The CLASP was capable of identifying finely granular behavior for multiple loads that could prove detrimental for the equipment and increase the electricity bill.

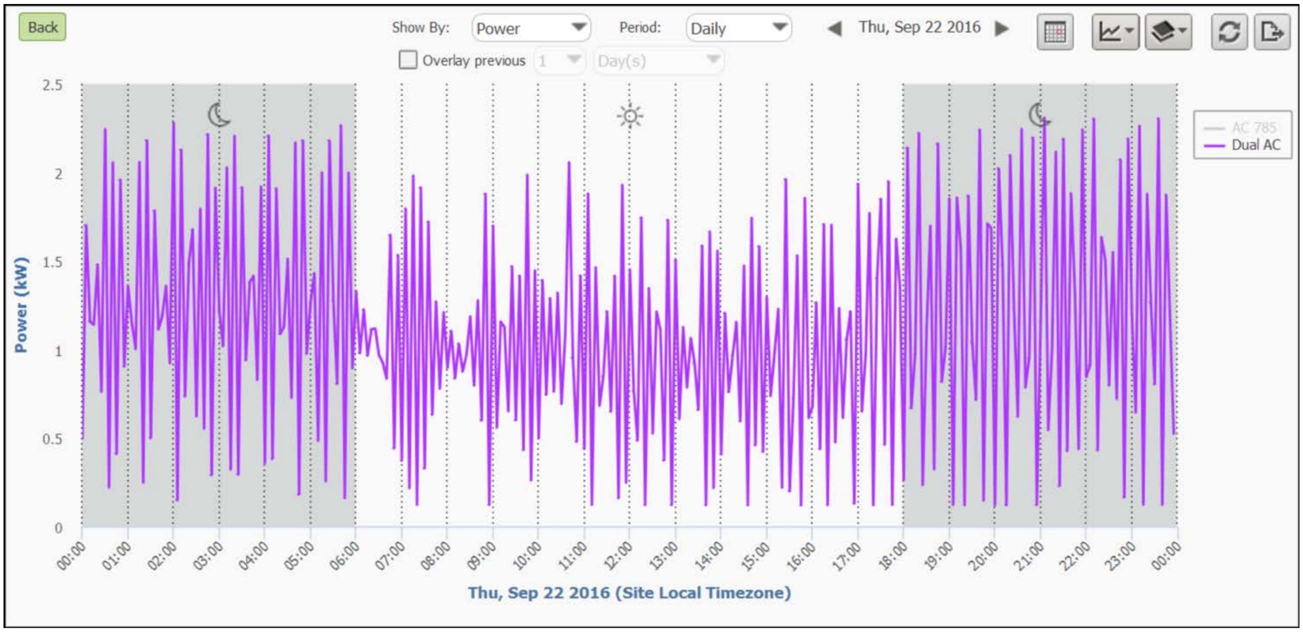


Figure 15: Dual AC short-cycling

c. Summary of Cost-Effectiveness Assessment

As noted above, assessing the cost-effectiveness of the technology is inherently difficult due to the fact that CLASP provides data (and analysis via the user interface) but does not provide direct energy or cost savings. The opportunities identified will vary widely based on the building in which they are installed, and actualization of any savings identified will depend on actions being taken by the building manager or facilities operation staff. For this case study, the CLASP readings could provide valuable and actionable insights to the building manager during the project, and analysis of a single ECM identified using the CLASP system (shutting down one of two central chillers during winter months) could cover approximately 87% of the energy cost savings required to make this CLASP system life cycle cost-effective (assuming a typical installation cost for a 180,000 ft^2 building).

Additionally, the following equipment behavior was identified using the CLASP: (1) short-cycling of air conditioning loads, (2) air conditioning loads not correlated with outside temperature, (3) uncoordinated behavior between condenser and AHU equipment, (4) permanent baseline consumption on both chillers, (5) potentially unnecessary HVAC operation during warm outdoor conditions, (6) cycling of lighting loads during off-hours, and (7) high energy consumption of lights during off-hours. The conditions identified here could prove detrimental for the equipment and increase-related electricity costs. For instance, short-cycling, if unmitigated, can significantly shorten the equipment's lifetime, increase energy consumption, and potentially fail to meet the zone's setpoint temperature.

IV. Summary Findings and Conclusions

A. OVERALL TECHNOLOGY ASSESSMENT AT DEMONSTRATION FACILITY

Installation of CLASP technology at the César E. Chávez Memorial Building successfully met some, but not all, of the performance objectives laid out in the demonstration plan. The system did not meet the test criteria for accuracy of either the laboratory or site deployment, as some of the tests did not achieve a ±2% accuracy (for the laboratory) or ±10% accuracy goal (for the field deployment). The system did exceed the test criteria for ease of deployment and integration with existing GSA enterprise systems, such as GSA Link. It also provides ample evidence that this system could meet cost-effectiveness objectives based on executing some of the ECMs identified by the system.

Three primary goals for studying this technology were established:

1. Enabling evaluation of building energy performance and achieving improvement in building operations, including identification of ECMs and FDD
2. Acquisition of accurate, high-resolution data and using those data as a driver for energy savings associated with occupant behavior change (e.g., tenant incentive programs)
3. Acquisition of accurate, high-resolution data for the purpose of tenant billing.

While the system does not appear to meet goals #2 and #3 because the accuracy targets were not able to be met in this case study, the system did perform successfully in addressing goal #1. Success in addressing goal #1 was demonstrated by utilizing CLASP to deliver key insights about specific device load profiles at the César E. Chávez Memorial Building. Based on the ECMs identified through the CLASP system, the building manager could reprogram one of the chillers to shut down during the non-cooling season—effectively reducing stand-by power consumption—and could reduce additional equipment maintenance and energy costs. Goal #1 was also met through successful demonstration of integrating CLASP data into the GSA Link software component SkySpark. This capability would enable ongoing FDD on devices monitored by CLASP. This would enable monitoring of lighting and plug load devices, which adds two significant end uses to the FDD capability provided by GSA Link and would enable additional rule sets based on power consumption of devices. Demonstration of CLASP data integration expands the opportunities for FDD across the GSA portfolio.

- For buildings with an existing GSA Link deployment, this would enable monitoring of additional end uses.
- For buildings that do not have GSA Link deployed, the GSA SkySpark platform could be used with CLASP data. This would provide an FDD capability for these buildings (albeit with reduced functionality) without full BAS integration and GSA Link deployment.
- Finally, this approach would deliver FDD functionality for buildings where a centralized BAS does not exist, enabling FDD for a set of GSA buildings that would not have this capability otherwise.

We have shown that CLASP can provide insightful high-resolution data as outlined in the performance objectives. With this information, the building manager can (1) identify ECMs leading to measurable savings and (2) address identified ECMs, thereby reducing the utility costs and saving energy.

B. LESSONS LEARNED AND BEST PRACTICES

The key lessons learned during this demonstration include:

- Wireless CT configuration and deployment tool software enabled very efficient deployment of this CLASP.
- The CLASP's deployment tool streamlined and organized the installation; it helped debug any problems with sensors at the time of installation as it provided real-time feedback.
- The use of a static voltage and power factor assumption can lead to reduced data accuracy and does not produce data of high enough accuracy to be used in tenant billing applications. This may be able to be addressed by utilization of the CLASP configuration with a voltage tap for billing applications. While the voltage tap did not significantly improve accuracy in this analysis, technically this should result in improved accuracy (as documented by the combined CT/meter testing procedure).
- When entering voltage and power factor assumptions, it is imperative to enter the best estimate possible because this will impact data accuracy. This step might require some previous knowledge of voltage level and power factor at the panel main or could benefit from spot checking with appropriate metering.
- Access to and utilization of the CLASP data can be achieved either through the native user application provided by the vendor or by API access. The API access enables integration of CLASP data into existing analytics platforms, such as GSA Link.
- Identification of the circuits for observation can be a time-intensive process. It is important to have clear goals as to the site's monitoring objectives prior to deployment.
- If using a single CT on a three-phase equipment, the load should be well balanced. This could be achieved through knowledge of the specific load or spot check of amperage.
- It is not always easy or possible to identify clearly which loads are associated with which circuits. This can result from inaccurate panel schedules, obscure naming conventions, or lack of circuit tracing. This is important to consider when trying to isolate monitoring to a specific tenant, space, or set of devices. Circuit tracing can be executed to clearly match all loads to panel circuits, though this may be an expensive process for locations with many low-load receptacles.
- A registered electrician will be required to install the system in accordance with site safety requirements. Special attention should be given to the installation of the voltage tap, where required.

C. DEPLOYMENT RECOMMENDATIONS

The CLASP system was installed in an existing building. However, it could have been implemented in a new construction just as easily. The acquisition system is flexible and allows single or three-phase panels, multiple voltage configurations (e.g., 120 V, 240 V, or 480 V), and power levels with their series of sensors (e.g., PAN-14 for amperage greater than 225 A).

The bridge collects sensor information at fast rates and must be installed in the vicinity of the panel box to ensure smooth communication and avoid package drops. Furthermore, the bridge requires strong Wi-Fi or cell signals to avoid package drops and missing readings. Heavy concrete construction, metal enclosures, and interference from other wireless sources could reduce signal strength. If the signal is weak, NREL recommends installing an extender for Wi-Fi and choosing a wireless carrier that provides a strong signal in the case of cell coverage. While connection to the LAN will entail cyber security approval (and associated challenges), this would, in theory, provide the most reliable delivery of data from the CLASP to its cloud-storage database.

To decrease measurement uncertainty, it is recommended to size CTs to estimated power levels (if possible), as opposed to rated breaker values. This may be achieved by metering current with a clamp ammeter to estimate amperage draw and effectively size the CT accordingly. Caution should be exercised to avoid under-sizing the CT because it might lead to inaccurate readings and, eventually, a damaged CT.

CLASP technology has applicability throughout the GSA portfolio. It will provide the most value where specific devices or end uses can be identified as requiring accurate power data. For example, devices with high power consumption, devices with uncertain schedules, and tenant-owned equipment are all scenarios where CLASP technology will deliver significant insight and has the potential to drive more significant savings. In addition, loads and devices that are not integrated into the BAS may be worth considering for monitoring via CLASP. This technology provides the capability to apply FDD to those systems where typically they are not monitored on an ongoing basis.

V. Appendices

A. MANUFACTURER CUT SHEET

Table 11: Manufacturer's Specifications for PAN-10 and PAN-12

Specifications	PAN-10 (63 A)	PAN-12 (225 A)
Physical Dimensions	17 x 20 x 32 mm 0.67 x 0.79 x 1.26 inch	46.2 x 22.8 x 32.6 mm 1.82 x 0.90 x 1.28 inch
Max Hot-Wire Outer Diameter (Including Insulation)	7 mm 0.28 inch	18 mm 0.74 inch
Current Measurement Range	0–63 A	0–225 A
Current Measurement Accuracy (Typical, at 25°C)	<2% at I>1 A	<2% at I>1 A
AC Frequency Supported	50 Hz (EU version) 60 Hz (U.S. version)	50 Hz (EU version) 60 Hz (U.S. version)
Transmission Frequency	434 MHz (EU) 915 MHz (U.S.)	434 MHz (EU) 915 MHz (U.S.)
Transmission Power (ERP)	0 dBm (max)	0 dBm (max)
Transmission Interval	10 seconds	10 seconds
Safety and EMC Certificates	U.S. & Canada Safety: UL-61010-1 (ETL listed), CSA- C22.2 EMC/Radio: FCC Part 15 subpart B, C Europe Safety: EN-61010-1 (CE)	U.S. & Canada Safety: UL-61010-1 (ETL listed), CSA- C22.2 EMC/Radio: FCC Part 15 subpart B, C Europe Safety: EN-61010-1 (CE)

	EMC: EN-ETSI 301489-3 Radio: EN-ETSI 300220-1	EMC: EN-ETSI 301489-3 Radio: EN-ETSI 300220-1
Flammability Rating of External Enclosure	UL94 V-0	UL94 V-0
Operating Temperature	0–50° C	0–50° C
Storage Temperature	20–65° C	20–65° C

Table 12: Manufacturer's Specifications for PAN-14

Specifications	PAN-14
Physical Dimensions	33.8 x 29 x 42.5 mm 1.33 x 1.14 x 1.67 inch
Current Input Range (From External Current Transformer)	0–5 $\mathrm{A}_{\mathrm{RMS}}$ (up to 10 A peak)
Current Measurement Range	Any applicable range based on CT ratio
Current Measurement Accuracy (Typical, at 25°C)	<2% at I >2% of full-scale current
Minimum Operating Current (at Input from External Current Transformer)	0.03–0.05 A
AC Frequency Supported	50 Hz (EU version) 60 Hz (U.S. version)
Transmission Frequency	434 MHz (EU) 915 MHz (U.S.)

Transmission Power (ERP)	0 dBm (Max)
Transmission Interval	10 seconds
Safety and EMC Certificates	U.S. & Canada Safety: UL 61010 1 (2012, 3rd Edition), UL 61010 2 030 (1st Edition), CAN/CSA C22.2 No. 61010 1 (2012, 3rd Edition), CAN/CSA C22.2 No. 61010 2 030 (1st Edition) (ETL listed) EMC/Radio: FCC Part 15 subpart B, C Europe Safety: EN 61010 1:2010 (3rd Edition), EN 61010 2 030:2010 (1st Edition) (CE) EMC: EN ETSI 301489 3 Radio: EN ETSI 300220 1 World Safety: CB Certification by Intertek, IEC 61010 1:2010 (3rd Edition), IEC 61010 2 030:2010 (1st Edition)
Flammability Rating of External Enclosure	UL94 V 0
Operating Temperature	0–50° C
Storage Temperature	20–65° C

Table 13: Complete Manufacturer's Specifications for PAN-42

Specifications	PAN-42
Pulse Output	Two optically isolated outputs for active and reactive energy (kWh)
Transmission Frequency	434 MHz (EU) 915 MHz (U.S.)
Transmission Power (ERP)	0 dBm (Max)
Transmission Interval	10 seconds
Safety and EMC Certificates	U.S. & Canada Safety: UL 61010 1, CSA C22.2 (ETL listed) EMC/Radio: FCC Part 15 subpart B, C Europe Safety: EN 61010-1 (CE) EMC: EN-ETSI 301489-3 Radio: EN-ETSI 300220-1
Dimensions **Weight** **Mounting Options**	110.3 x 81 x 37.2 mm 4.34 x 3.19 x 1.46 inch 200 g Wall mount or DIN top hat rail EN50022
Flammability Rating of External Enclosure	UL94 V
Operating Temperature	0–50° C (32–122° F)
Storage Temperature	-20–65° C (-4–149° F)
Display	Three LEDs for phase indications and additional LED for online status indication