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Transactive Campus Energy Systems

Final Report

September 2017

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U.S. DEPARTMENT OF ENERGY

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Summary

Transactive energy refers to the combination of economic and control techniques to improve grid reliability and efficiency. The fundamental purpose of transactive energy management is to seamlessly coordinate the operation of large numbers of new intelligent assets—such as distributed solar, energy storage and responsive building loads—to provide the flexibility needed to operate the power grid reliably and at minimum cost, particularly one filled with intermittent renewable generation such as the Pacific Northwest. It addresses the key challenge of providing smooth, stable, and predictable "control" of these assets, despite the fact that most are neither owned nor directly controlled by the power grid.

The Clean Energy and Transactive Campus (CETC) work described in this report was done as part of a Cooperative Research and Development Agreement (CRADA) between the U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL) and the Washington State Department of Commerce (Commerce) through the Clean Energy Fund (CEF). The project team consisted of PNNL, the University of Washington (UW) and Washington State University (WSU), to connect the PNNL, UW, and WSU campuses to form a multi-campus testbed for transaction-based energy management—transactive—solutions. Building on the foundational transactive system established by the Pacific Northwest Smart Grid Demonstration (PNWSGD), the purpose of the project was to construct the testbed as both a regional flexibility resource and as a platform for research and development (R&D) on buildings/grid integration and information-based energy efficiency.

This report provides a summary of the various tasks performed under the CRADA. PNNL work involved the following major experiments and deployment of the network infrastructure to support the experiments:

1. All experiments on the PNNL campus and also at UW and WSU required the use of the transactional reference platform—VOLTTRON™, a PNNL-developed open-source software platform, which facilitates communicating with and controlling flexible building loads. PNNL developed a detailed network/computing infrastructure operations and security plan for the project. The plan describes the operational requirements, the cybersecurity requirements, network and infrastructure design, and cybersecurity and infrastructure testing.

2. Experiment: Transactive Control and Coordination (TCC)

   The premise of transaction-based control is that interactions between various components in a complex energy system can be controlled by negotiating immediate and contingent contracts on a regular basis in lieu of or in addition to the conventional command and control. Each device is given the ability to negotiate deals with its peers, suppliers, and customers to maximize revenues while minimizing costs.

   A typical building might have several chillers that supply a number of air handlers with chilled water on demand. If several air handlers require the full output of one chiller, and another air handler suddenly also requires additional cooling, traditional building control algorithms simply start up a second chiller to meet the demand and the building's electrical load increases upward accordingly. A transaction-based building control system behaves differently. Instead of honoring an absolute demand for more chilled water, the air handler requests such service in the form of a bid (expressed in dollars), increasing its bid in proportion to its "need" (divergence of the zone or supply air temperature from its set point). The chiller controls, with knowledge of the electric rate structure, can easily express the cost of service as the cost of the kilowatt hours (kWh) to run the additional chiller plus the incremental kilowatt (kW) demand charge (if it applies). If the zone

served by this air handler just began to require cooling, its "need" is not very great, so it places a low value on its bid for service and the additional chiller stays off until the level of need increases. Meanwhile, if another air handler satisfies its need for cooling, the cost of chilled water immediately drops below the bid price because a second chiller is no longer required, and the air handler awaiting service receives chilled water. Alternatively, a peer-to-peer transaction can take place in which an air handler with greater need for service displaces (literally outbids) another whose thermostat is nearly satisfied.

Experimental results show promise for the application of market-based controls in commercial building heating, ventilation, and air-conditioning (HVAC) systems. Savings were modest compared to results from previous simulations, but PNNL believes they can be improved. Some differences between experiment and simulation were expected due to a mismatch between the EnergyPlus™ model and the physical building, while many differences may likely be attributed to imperfect modeling of building dynamics. In simulation, decisions made by variable air volume (VAV) agents were acted upon immediately and control was perfect; in a physical experiment, control decisions were delayed, and control was imperfect.

3. Experiment: Intelligent Load Control (ILC)

To support transactive energy services or to mitigate short- or long-term imbalances between supply and demand or to manage building peak under traditional utility rate structures, available loads need to be prioritized for curtailment. ILC can be used to manage loads to a target (energy or cost) in a building or group of buildings using both quantitative and qualitative criteria. ILC uses an analytic hierarchy process to prioritize the loads for curtailment. Two main factors are used to deploy ILC: the rules that govern the prioritization of the loads and the target load. With a traditional utility rate structure, the goal is to lower the demand charge over the billing period, which is typically 1 month. Under this scenario, the building load has to be forecasted for the next billing period and a target selected. In the transactive energy world, where the price of electricity may be dynamic, the target also becomes dynamic. Under the dynamic pricing scenario, by anticipating the future price of energy, the process can consume more energy to precool or preheat when the prices are low. The ILC process can be applied to any controllable load (homogeneous and heterogeneous) in a building, such as rooftop units (RTUs), variable-air-volume boxes, and lighting. Furthermore, the ILC process can also be used to manage building loads based on an energy budget instead of a peak.

The ILC algorithm was initially tested in a simulation environment to control a group of RTUs to manage the building's peak demand while still keeping zone temperatures within acceptable deviations. After successful testing of the algorithm in the simulation environment, it was successfully deployed on a building on the PNNL campus. Field test results indicated that ILC managed the peak demand within an acceptable target peak level based on Whole Building Energy (WBE) prediction, as well as zone temperatures reflecting the comfort status of building occupants.

4. Experiment: Transactive Control—key enabler of increasing the hosting capacity of renewable energy generation

A significant increase of new generation is from distributed renewable sources. When these technologies form a significant (>20%) fraction of grid capacity, in a business-as-usual scenario, utilities will be forced to maintain a significant standby capacity to mitigate the imbalance between supply and demand. In this business-as-usual scenario, any loss of generation or short-term imbalance between supply and demand will be mitigated using standby generation. Because more than 75% of electricity consumption occurs in buildings, flexible loads (variable-frequency drives, hot water heaters, lights, etc.) in the buildings can be used mitigate the imbalance.

In this experiment, two transactive coordination strategies were proposed to manage flexible building loads for renewable integration. The study proved the theories that support the two transactive coordination strategies and discussed the associated tradeoffs between algorithm convergence rate and required amount of information exchange. This project focused on three types of flexible building loads—air handling unit, rooftop unit, and a population of water heaters. The study showed that coordination and control of flexible loads had great potential to integrate variable generation sources. The flexible loads could successfully track a power dispatch signal from the coordinator, while having little impact on the quality of service to the end-users.

5. Experiment: Automated Fault Detection and Diagnostics (AFDD) and Automated Identification of Retro-Commissioning (AIRCx) Opportunities

   Deploying multiple value streams (grid and energy efficiency services) on the VOLTTRON platform will increase the value proposition to the end-users and make the deployment of a transactive energy framework for buildings more cost-effective. An example of one such energy efficiency service is an operation and maintenance service of interest to buildings and third-party service providers; the service is used to maintain, repair, replace, and/or operate buildings and equipment within buildings, leading to enhancements in overall customer comfort and convenience.

   Today, many large (>100,000 ft^2) commercial buildings use building automation systems (BASs) to manage a wide range of equipment. Based on available information, many buildings consume between 10% and 30% of excess energy because they do not employ advanced control strategies; existing strategies are not properly managed, which leads to overrides and occupant discomfort. Several VOLTTRON applications have been designed, developed, and are being tested on buildings. These algorithms automatically identify the operational problem or an advanced control opportunity and report them to the building operator; or in some cases the algorithms have the ability to automatically self-correct the problem. The measures that can be automatically detected and corrected operational problems include schedule adjustments, damper minimum flow adjustments, thermostat adjustments, as well as dynamic resets to static pressure, supply-air temperature, condenser chilled- and hot-water temperatures, and chilled- and hot-water differential pressure set points. For this project, fourteen re-tuning measures were selected for automation.

In addition to the network infrastructure and experimental results, a major outcome for the PNNL work is a set of user guides that provide a “recipe” for replication of the PNNL experiments.

Acronyms and Abbreviations

AFDD	automated fault detection and diagnostics
AIRCx	Automated Identification of Retro-Commissioning
AHP	analytic hierarchy process
AHU	air-handling unit
BAS	building automation system
BESS	battery energy storage system
CEF	Clean Energy Fund
CETC	Clean Energy and Transactive Campus project
CI	continuous integration
Commerce	Washington State Department of Commerce
CRADA	Cooperative Research and Development Agreement
CSV	comma-separated variable
DER	distributed energy resource
DOE	U.S. Department of Energy
DOE-EERE	U.S. Department of Energy Office of Energy Efficiency and Renewable Energy
DOE-OE	U.S. Department of Energy Office of Electricity Delivery and Energy Reliability
EIOC	Electricity Infrastructure Operations Center
HIL	hardware-in-the-loop
HVAC	heating, ventilation, and air-conditioning
ILC	intelligent load control
PNNL	Pacific Northwest National Laboratory
PV	photovoltaic
RCx	retro-commissioning
R&D	research and development
RTU	rooftop unit
SAT	supply-air temperature
TCC	transactive controls and coordination
TCL	thermostatically controlled load
UW	University of Washington
VAV	variable air volume
WBE	Whole Building Energy
WSU	Washington State University

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1.0 Introduction

Transactive energy refers to the combination of economic and control techniques to improve grid reliability and efficiency.[1] The fundamental purpose of transactive energy management is to seamlessly coordinate the operation of large numbers of new intelligent grid assets—such as distributed solar energy, wind energy, energy storage, and responsive building loads—to provide the flexibility needed to operate the power grid reliably and at minimum cost, particularly a grid system filled with intermittent renewable generation, as in the Pacific Northwest. Transactive energy management addresses the key challenge of providing smooth, stable, and predictable "control" of these assets, despite the fact that most are neither owned nor controlled by the power grid.

As a demonstration of real-world transactive energy management, the Clean Energy and Transactive Campus (CETC) project is jointly funded by the U.S. Department of Energy (DOE) and the Washington State Department of Commerce (Commerce) through the Clean Energy Fund (CEF). Under a Cooperative Research and Development Agreement (CRADA), Pacific Northwest National Laboratory (PNNL), Washington State University (WSU), and the University of Washington (UW) have teamed to form this multi-campus CETC and network to conduct research that advances transactive control of distributed energy resources (DERs).

The goals of the CETC span DOE Office of Energy Efficiency and Renewable Energy (DOE-EERE) programs, yet the common denominator is the buildings' role:

- Beyond demand response—enable buildings, fleets of equipment, and other building assets to deliver services to the grid while maximizing energy efficiency for the owners.

  "How can we control equipment within a distribution feeder to deliver valuable services to the owners and operators of buildings and the grid simultaneously?"

- Grid scale, right-sized storage—enable buildings to function as "virtual" storage devices thereby reducing the total capacity of grid storage needed to meet the needs of a utility.

  "How can utilize building loads and control of equipment to lessen the physical storage we need to satisfy the utility?"

- Behind the meter response to photovoltaics (PV) variability—lessen, dampen, and otherwise minimize the effects of building and site sighted PV as seen by the utility.

  "How can we utilize groups of buildings and loads to make site installed PV appear as a non-variable generation source to the utility?"

Although the ultimate objective of this research will address coordination at four physical scales: single building, single campus, multi-campus, and community micro-grid, this first phase of the work only demonstrated energy efficiency and transactive controls at the building scale to support research that advances the state of knowledge in three key areas of critical interest to DOE:

- PNNL—transactive energy management for building and campus energy efficiency. PNNL will utilize the Electricity Infrastructure Operations Center (EIOC) in its new Systems Engineering

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[1] GridWise Architecture Council. January 2015. *GridWise Transactive Energy Framework Version 1.0*. PNNL-22946 Ver 1.0. http://www.gridwiseac.org/pdfs/te_framework_report_pnnl-22946.pdf

Building as both the nerve center for the multi-campus demonstration and as a building controls laboratory. This infrastructure, along with additional PNNL buildings and connections to resources at UW and WSU, will be used to support the development and testing of transactive energy management systems and establish a federated Smart Campus testbed.

- UW—transactive coordination of campus assets to support integration of PV and provide energy efficiency benefits. UW will connect smart inverters to PV panels to be installed at multiple sites on the campus by the University, as well as add a lithium-ion based battery energy storage system (BESS) to be connected to the campus electrical distribution system. It will leverage its expertise in data analytics to develop tools to analyze the data collected from these panels as well as from the instrumented buildings on the PNNL campus. It will use its expertise in control to help PNNL develop control strategies for making buildings responsive to transactive control signals. Finally, it will develop techniques and tools to optimize the operation of the battery in conjunction with the campus electrical load, the production of the PV panels, and transactive control signals.

- WSU—transactive control of a campus-scale micro-grid connected to a community distribution system to explore "smart city" and grid resiliency concepts. WSU will invest in linking its new control center testbed with an energy management system and distribution management system through its Smart Cities initiative, which leverages Avista and WSU investments in the WSU microgrid and Pullman (WA) distribution infrastructures. It also leverages recent funding from the M. J. Murdock Charitable Trust that allows WSU to extend the testbed to include simulation capabilities for renewable devices, automation, and smart meters. The project at WSU will install new solar energy devices on within the Pullman smart city footprint, as well as tools for planning, operation, and control of resilient distribution systems, transactive dispatch, and consumer engagement—taken together, elements critical for development of smart grids in society.

PNNL utilized the campus testbed as a platform for conducting research and development (R&D) on the management of campuses and buildings as a regional grid resource based on a transactive energy management approach. It developed transactive control strategies for campus buildings and embedded them in VOLTTRON™ controllers that interfaced with their existing control systems. PNNL's work involved four major experiments and deployment of the network infrastructure to support the experiments. The major outcome for the PNNL work is a set of user guides that provides a "recipe" for replication of experiments to help utilities, municipalities, and building owners who are facing larger deployments of clean energy technologies, aging infrastructure, and new regulations.

This report is organized as follows: Section 2.0 provides a summary of the infrastructure; Section 3.0 summarizes the transactive control and coordination experiment; Section 4.0 presents a summary of the intelligent load control experiment; Section 5.0 provides a summary of the renewable integration experiment; Section 6.0 summarizes the automated fault detection diagnostics and automated commissioning experiment; Section 7.0 summarizes the work conducted at UW and WSU; Section 8.0 addresses inventions; and Section 9.0 summarizes the CRADA project.

2.0 Infrastructure

In order to demonstrate transaction-based controls to provide energy efficiency services and grid services, the project utilized VOLTTRON, a distributed sensing and control platform, to host both energy efficiency and grid services. The energy efficiency services include automated fault detection and diagnostics (AFDD) and self-correcting controls applications for heating, ventilation, and air conditioning (HVAC) equipment. The grid services include mitigation of short-term supply and demand imbalance from significant penetration of distributed PV and transactive controls applications that make use of utility signals to respond and control building systems (e.g., HVAC, lighting, etc.). Multiple VOLTTRON nodes were installed in each building, which were used to collect data from the building systems to demonstrate new control methods that use transactive energy concepts. The project also outfitted one of the control rooms in PNNL's EIOC with the hardware and software capabilities needed to serve as the Operations Center for the multi-campus project.

This section describes the networking and computing infrastructure operations and cyber security implementation required to deploy the CETC project, along with the infrastructure investments made within the EIOC.

2.1 VOLTTRON Infrastructure

All experiments on the PNNL campus, and also at UW and WSU, required the use of the transactional reference platform—VOLTTRON. PNNL developed a detailed network/computing infrastructure operations and security plan for the project. The plan described the operational requirements, the cybersecurity requirements, network and infrastructure design, and cybersecurity and infrastructure testing.

Based on the project infrastructure and security requirements, and combined with the past experience of the VOLTTRON team, a network infrastructure was designed (Figure 1). The CETC project infrastructure is divided into four groups: Campus, Project Data Collection and Analysis, Project Operations, and Project Development, which are described in the following subsections. The network infrastructure has been fully designed, implemented, and operational. The deployment has been reliable and secure while maintaining the flexible environment that is necessary for an evolving project.

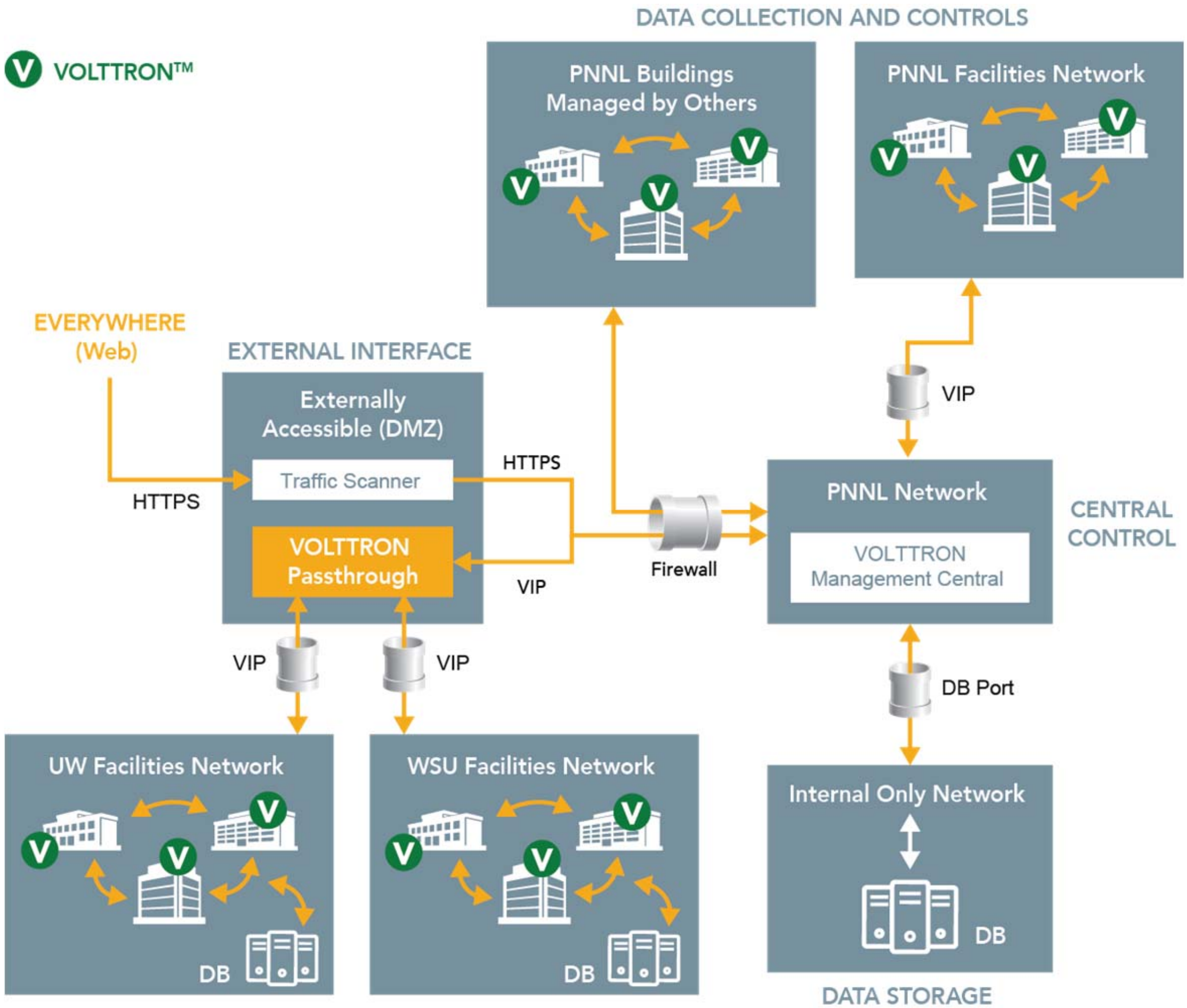

Figure 1. The CETC VOLTTRON Network Infrastructure

2.1.1 Campus Infrastructure

For the CETC project, the campus infrastructure consisted of devices (e.g., rooftop units, building systems, meters, solar panels) deployed at PNNL, WSU, and UW.

PNNL assisted the other sites in setting up their VOLTTRON instances for collection. Data collected by PNNL is forwarded to external collaborators for their use, as seen in Figure 1.

The PNNL team used a configuration management and software deployment program to manage the campus infrastructure through a secure tunnel established via the management interface. Such a managed deployment allowed the project team to ensure experiment and data integrity.

2.1.2 Project Data Collection and Analysis Infrastructure

CETC project data collection and analysis infrastructure was hosted at PNNL using database replication and backups to prevent data loss. CETC project data collection and analysis infrastructure provides the following services:

- The final data storage location for all facilities and experiment data using the VOLTTRON historian backend.
- User interface for all web-based data analytics and visualization applications.
- Computing infrastructure for any large-scale data analysis applications.
- VOLTTRON Management Central Instance that serves and manages all of the deployed VOLTTRON instances.

2.1.3 Project Operations Monitoring Infrastructure

In addition to data from the experiments, PNNL collected operational data in order to aid the project team in determining the health and security of the project computing infrastructure.

For project resources located at PNNL, all system, security, and other logs were sent to the VOLTTRON index in Splunk, which is a software platform that allows users to search, analyze, and visualize machine-generated data. Firewall reports are regularly sent to the VOLTTRON team for analysis and detection of any potential issues.

2.1.4 Project Development Infrastructure

The project development infrastructure within VOLTTRON contains a continuous integration (CI) environment, which builds the platform, tests it, and notifies the project team of success or failure. For each branch pushed to the GitHub repository, the CI builds and runs integration tests on all core agents. Agents were evaluated to ensure they functioned as expected (i.e., start, communicate with the running platform for any agent services required, and stop). Once integration tests were run successfully, the core was moved into multiple staging environments. These environments mimicked the expected production environments as closely as possible. A mixture of real and simulated sensors was available to read from in the staging environments, allowing for the comparison of different environments.

2.2 Electricity Infrastructure Operations Center

Infrastructure investments through the CRADA were also made within PNNL's EIOC so that it could be utilized as the regional nerve center for the multi-campus demonstration. The EIOC is dedicated to the advancement of electric grid operations research as shown in Figure 2 and Figure 3. Since 2015, PNNL has been involved in extensive updates to the EIOC, including relocating the facility to a more useful and secure building. The EIOC now has a dedicated control room for managing bulk power transmission and another control room for managing power distribution. Monitor walls and a configurable, multiplexing video software allow the EIOC to easily switch displays in and between the two control rooms. The EIOC has enabled cutting-edge research on control room interactions and dynamics with both humans-in-the-loop and hardware-in-the-loop. The EIOC provides the infrastructure used to visualize the current load and available flexibility for all the campuses, manage the transactive network, and monitor the overall performance of the transactive algorithms and individual resources on each campus. It is being used to manage the conduct of each CETC experiment or demonstration and archive the operational data collected from them.

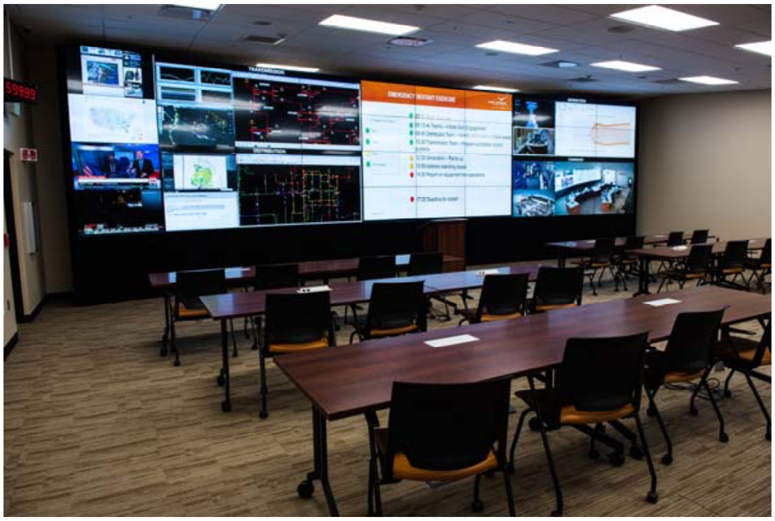

Figure 2. EIOC East Control Room

Figure 3. EIOC West Control Room

3.0 Transactive Control and Coordination Experiment Summary

The transactive control and coordination (TCC) experiment addressed the CETC goal “beyond demand response” through the development, deployment, and testing of control algorithms that respond to price or grid signals to deliver solutions that satisfy various grid, user, energy, and societal market use cases.

Market-based control, an example of transactive control, is a distributed control strategy. In a market-based control system, a virtual market enables transactions between HVAC components for the exchange of “commodities,” such as electricity power or cooling/heating energy. Each component is represented by a VOLTTRON agent that is self-interested and tends to maximize its own benefit. Agents submit bids for commodities based on the benefit they receive. The market receives bids from all agents and determines the clearing price of the commodity. Each agent then adjusts its consumption based on the cleared price. Market-based control is distributed and scalable, making it suitable for large-scale applications.

Markets are defined within a building according to commodity (e.g., cooled air), physical relationship (e.g., all variable air volume [VAV] boxes connected to an air handler), or some combination thereof. In this work, PNNL has taken this concept and created a market in a commercial building HVAC system that allows zones to bid for cooling energy with the air handler and chiller, which then bids for electricity from the electric market to generate the necessary amount of cooling. The purpose of this system is to expose the building’s inherent electric demand flexibility, and thus allow integration of building operation with power system operation. The structure of our market is bi-level—both cooled air and electricity are commodities. VAV agents, representing the thermal zones needing cooled air for conditioning, purchase the cooled air from the AirMarket. This market has a single supplier, the AHUChiller agent, which in turn purchases the electricity it requires to generate the cooled air from the ElectricityMarket. The ElectricityMeter supplies electricity to the ElectricityMarket.

The control system is composed of a set of models, each representing separate conditioned areas, equipment, and markets. Models are control-oriented models—all of which are inverse models—and are therefore relatively simple compared to those used in detailed energy simulation. The developed models include 1) a zone model to predict the HVAC energy demand based on outdoor dry-bulb temperature and other zone parameters, 2) an air handler model used to estimate fan power and cooling load given real-time measurements from the building automation system, 3) a simple chiller model that estimates the electric demand of the district chilled water plant required to serve the cooling load calculated by the air handling unit, and 4) a set of rooftop unit (RTU) models for the future deployment of transactive controls to commercial buildings that have one or more zones conditioned by packaged rooftop heat pumps.

Simulations of transactive controls were performed using a new co-simulation capability developed for this project. This new co-simulation capability, built upon the VOLTTRON platform, allows testing and validation of the developed algorithms against PNNL’s EnergyPlus building simulation model within the target deployment environment. A VOLTTRON agent was developed to manage communication between the VOLTTRON message bus and the EnergyPlus simulation engine. PNNL has validated the VOLTTRON-based market application against previous simulation cases using this capability.

The first simulation case used a fixed price to test market operation independent of changes in price from one clearing interval to the next. With a relatively higher price, this case resulted in demand reduction and energy savings. In the second case of demand-limiting, PNNL imposed a demand limit to the total (fan plus chiller) electric demand at each market-clearing interval. The third case of responding to a dynamic price case tested the ability of the market and building to react to price signals that changed over time.

These market-based controls have been deployed in a small commercial building on the PNNL campus to test the market-based controls in a physical system. Each agent was configured to receive measured real-time values from the building automation system (BAS). These values set the state of the models so that calculations—and thus market bids—reflected current conditions. VAV agents controlled the cooling set points in occupied, standby, and unoccupied modes strictly within limits established by the building manager. Two types of experiments were performed, corresponding to the fixed price and demand-limiting cases explored in simulations.

PNNL evaluated the performance of the market-based controls during the physical tests using two methods: 1) a simple, naïve approach that compares experimental results from performance measured during a similar "baseline" day, and 2) a statistical approach that attempts to model building performance based on a set of relevant predictors selected by their association with the underlying physical processes that determine building energy use. Results from these experiments generally supported previous findings from simulation studies and provided insights for further improvement.

Experimental results show promise for the application of market-based controls in commercial building HVAC systems. Savings were modest compared to results from previous simulations, but PNNL believes they can be improved. Some differences between experiments and simulations were expected due to a mismatch between the EnergyPlus model and the physical building, while many differences may likely be attributed to imperfect modeling of building dynamics. In simulations, decisions made by VAV agents were acted upon immediately and control was perfect; in physical experiments, control decisions were delayed, and control was imperfect. Experimental results are described in more detail in Corbin et al. (2016).

4.0 Intelligent Load Control Experiment Summary

The intelligent load control (ILC) experiment addressed the CETC goal "Beyond demand response" by managing buildings against an energy budget and resource constrained operations. The focus of the ILC experiment was to develop, valuate, and demonstrate that ILC can be deployed to minimize the chance of high demand charges and reduce negative effect to the electric grid. The ILC algorithm that was developed can be implemented to achieve peak demand reduction while minimizing impacts on occupant comfort. The algorithm was designed to minimize the additional sensors and minimum configuration requirements to enable a scalable and cost-effective implementation for both large and small-/medium-sized commercial buildings. The ILC algorithm uses an analytic hierarchy process (AHP) to dynamically prioritize the available curtailable loads based on both quantitative (deviation of zone conditions from set point) and qualitative rules (types of zone). After the demand response event has ended, the curtailed loads are likely to turn on simultaneously once normal control resumes. The ILC enables the curtailed system to coordinate and provide the intelligent restoration of curtailed systems, thereby reducing the change of post-demand response. By anticipating future demand, the ILC process can be extended to add advanced control features such as precooling and preheating to alleviate comfort issues when operation of the RTUs is curtailed to manage the peak demand. The ILC algorithm can be implemented on low-cost single-board computers (e.g., Raspberry PI, BeagleBone, etc.).

The ILC algorithm was initially tested in a simulation environment to control a group of RTUs to manage the building's peak demand while still keeping zone temperatures within acceptable deviations. After successful testing of the algorithm in the simulation environment, PNNL implemented and demonstrated the ILC agent using VOLTTRON to manage the electric demand in a test building on the PNNL campus. To support (1) traditional utility rate structure and (2) capacity bidding program, the target peak demand level can be proactively adjusted to a realistically attainable level, even before that level of demand has actually been reached. The ILC, using target levels estimated by Whole Building Energy (WBE) or 10-Day average baseline, was tested under different outdoor operating conditions. Based on the test results, the ILC was successful in coordinating how many RTUs run concurrently, thereby maintaining the building peak demand to the target level based on the load forecast without a significant reduction in occupant comfort.

By anticipating future demand, the process can be extended to add advanced control features such as precooling and preheating to alleviate comfort issues when the RTUs are curtailed to manage the peak demand. Although the ILC process was highly tailored to work with RTUs, it can be generalized and applied to any controllable loads in a building, such as those of VAV boxes and lighting. Furthermore, the ILC process can be extended to manage building loads based on an energy budget instead of peak consumption. Experimental results are described in more detail in Kim et al. (2016).

5.0 Renewable Integration Experiment Summary

The renewable integration experiment addressed the CETC goal “Behind the meter response to PV” through the development of experiments to mitigate short- and long-term imbalance from distributed renewable generation. This experiment involved coordinating and controlling power consumption of flexible loads to mitigate the power fluctuation of the solar PV panel without affecting the quality of service to the end-users.

Vast integration of variable generation sources brings a significant amount of uncertainty to the power grid, and presents a daunting challenge to current power system operation and control. Maintaining the power balance with variable renewables is one of the most important problems in smart grid research. Traditionally, the variability of renewables has been handled through supply-side (generation) reserves. This experiment seeks to employ building loads to reduce the need for supply-side measures.

Building loads such as commercial building HVAC systems, residential thermostatically controlled loads (TCLs), electric vehicles, and deferrable appliance loads are excellent flexible resources for absorbing the variability of renewable generations. For example, by changing the supply fan speed of an HVAC system, its power deviation from baseline can be made to track the power deviation of a solar PV panel, thus mitigating its power output variability. This experiment investigated integration of variable generation sources into the grid by aggregating, coordinating, and controlling distributed demand-side resources.

Building on the fan example in the previous paragraph, to fully exploit the potential of various classes of demand-side resources, it is essential to study optimal coordination of multiple flexible loads considering their diversified response characteristics and availability. Renewable integration aims to use various types of flexible building loads to locally absorb the variability of renewables so that less power fluctuation is injected into the power grid.

Two distributed transactive coordination strategies (an iterative method based on dual decomposition and a one-shot supply function bidding method) were proposed to engage self-interested responsive loads to provide services to the grid. PNNL compared the solutions obtained from the two methods with that solved using a centralized approach. This showed that these two different approaches were equivalent, and they both converged to the same optimal solution. However, there was a conservation of complexity in the two transactive coordination strategies, in terms of algorithm convergence rate and the amount of information needing to be exchanged. The iterative method based on dual decomposition required multiple iterations between the loads and coordinator before reaching the optimal solution, but the only information needing exchange was the price and quantity of the service. The supply function bidding method was able to clear the market in one shot, but each responsive load must bid a supply curve, which is a function representing the load’s willingness to provide different amounts of services at different prices.

Based on the resources that are available, three types of flexible building loads were chosen for this renewable integration experiment: 1) a supply fan in an air-handling unit (AHU), 2) a supply fan in an RTU, and 3) a collection of water heaters. Control of these three types of building loads to compensate the solar generation deviation of a solar PV panel on the PNNL campus was demonstrated. The overall objective of the experiment was to coordinate and control power consumption of flexible loads to mitigate the power fluctuation of a solar PV panel without affecting the quality of service to the end-users. Moreover, the testbed infrastructure was based on VOLTTRON, which facilitated communicating with and controlling flexible building loads. Although the focus is on the three specific types of building loads for the purpose of renewable integration, the developed coordination and control algorithm and the testbed infrastructure can also be adopted to provide other building-to-grid functions.

In summary, the results showed that each of the three types of available loads at PNNL (i.e., AHU, RTU, and water heaters) were able to track the power fluctuations of an onsite solar PV panel on the PNNL campus. Moreover, the experiment demonstrated that by providing services to the grid, there was little impact on the thermal comfort of the end-users. This work involved experiment-based, simulation-based, and hardware-in-the-loop (HIL)-based demonstrations. Experimental results are described in more detail in Hao et al. (2016).

6.0 Automated Fault Detection Diagnostics and Automated Commissioning Summary

The AFDD and automated identification of retro-commissioning (AIRCx) experiment addressed the CETC goal "beyond demand response" by validating and scaling proactive controls—controls that adaptively learn, and automatically commission and run "calisthenics" to improve operating efficiency of the equipment.

Today, many large (>100,000 ft^2) commercial buildings use sophisticated BASs to manage a wide range of building HVAC equipment. While the capabilities of BASs have increased over time, many buildings still do not fully use their capabilities and are not properly commissioned, operated, or maintained. This leads to inefficient operations, increased energy use and cost, and reduced lifetimes of the equipment. Periodically "tuning" buildings ensures maximum building energy efficiency and the comfort of building occupants. A poorly tuned system can (but does not always) maintain comfortable conditions but at a higher energy cost to overcome inefficiencies.

In many cases, the BAS controls were never configured properly to "optimize" set points. Often, set points are configured to respond to worst-case outdoor-air conditions (or design conditions), instead of internal zone conditions. Equipment vendors often use outdated "rules of thumb" that do not allow their equipment to be "optimized" or sequenced properly. Older buildings with BASs are often configured to have their controls respond to sequences that are no longer relevant because equipment with better performance is installed, building envelopes (newer windows, roof, etc.) are improved, or other similar changes occur. Human factors also effect building performance and necessitate the need for building re-tuning. These human factors can include space loading and mission (use) changes; poorly trained operations staff, who often make the final determination on how to operate the various systems (including manual set points and overrides); or poorly designed systems (sizing, control sequences, etc.).

BASs have been sold as an improvement over mechanical (pneumatic) controls and electric/electronic controls with the promise of better control response, more accurate sensing, and the ability to operate with fewer human resources. While this is true, many BASs are often found with fixed set point values, modified alarm settings (that no longer provide alarms when equipment or systems are not operating as designed), numerous overrides on equipment schedules, set points, commanded values, and other man-made anomalies. Within a short period of time (often within a few months after BAS installation), these BAS operational changes become the "legacy" (standard) mode of operation. This mode of operation cannot succeed in "optimizing" building systems and equipment or in creating improvements that are sustained or significant.

There is general agreement that retro-commissioning (RCx)[1] of existing buildings saves energy; most reported savings are in in the range of 10% to 30% of the total building energy consumption. However, RCx as it is practiced today is perceived as not being cost-effective and also does not guarantee persistence of optimum building operations. Many of the operational problems typically detected during the RCx process can be detected automatically and continuously day-to-day, thereby allowing the buildings to operate near optimally. PNNL developed a re-tuning process to address some of the issues associated with RCx. However, to ensure persistence of optimum building operations, the re-tuning process has to be applied periodically. The algorithms described in the experiment will allow continuous

[1] Commissioning is a systematic quality assurance process that spans the entire design and construction process, helping ensure that the new buildings' performance meets owners' expectations - http://www.documents.dgs.ca.gov/green/commissionguidenew.pdf.
Although a number of definitions of RCx exist, the commonly used definition is a systematic method for investigating how and why existing buildings' systems are operated and maintained and identifying ways to improve overall building performance.
http://www.documents.dgs.ca.gov/green/commissionguideexisting.pdf

and automatic re-tuning, thereby leading to and ensuring persistence of desired operations. These diagnostics will reduce the cost of implementing RCx.

Re-tuning is a systematic process of identifying and correcting operational problems that plague commercial buildings that have BASs. Correction of many of these problems requires no or very little cost. The problems identified as part of this process can include the following:

- excessive temperatures (too high, too low) for various HVAC systems, including supply-air, chilled-water, and hot-water systems
- overrides on set points and equipment (intended for short periods of time), but forgotten and left in place (for long periods of time)
- resets on set points for supply-air temperatures (SATs) and static pressures that are not working or are locked (too high, too low, fixed)
- resets on set points for chilled-water supply temperatures and chilled-water loop differential pressures that are not working or locked (too high, too low, fixed)
- resets on set points for heating hot-water supply temperatures and heating hot-water loop differential pressures that are not working or locked (too high, too low, fixed)
- equipment running under low load conditions (low delta-T—difference between supply and return water) for hot-water and chilled-water systems
- equipment running when the building is not occupied and there is no demand for those systems (AHU, chiller plant, heating hot-water plant, etc.).

Many operational problems identified during re-tuning can be detected automatically and continuously, allowing the buildings to operate near optimally, leading to lower RCx cost and increased persistence. A number of re-tuning measures can be detected automatically. Similar to a semi-automated/manual re-tuning process, the automation of detecting re-tuning measures for the re-tuning process relies upon analysis of real-time or near real-time data collected from the BAS to detect and diagnose operational problems that can be corrected with no- or low-cost actions. The automation of detecting these re-tuning measures has the potential to tap into 60% to 80% of the savings attributed to RCx with very little investment; it also ensures the long-term persistence of savings.

AIRCx uses computer algorithms to ensure that buildings operate continuously at peak efficiency. AIRCx ensures that the building staff focus on activities for which their intervention is essential (e.g., replacing components that have physically failed or degraded, thereby reducing efficiency and increasing the cost of operation) and corrects operational problems that can be corrected without operator intervention leading the way to self-healing control systems.

For this project, a total of 14 re-tuning measures were selected for automation:

- detection, diagnosis, and correction of high duct static pressure in VAV AHUs
- detection, diagnosis, and correction of low duct static pressure in VAV AHUs
- detection, diagnosis, and correction of high SAT in VAV AHUs
- detection, diagnosis, and correction of low SAT in VAV AHUs
- detection and diagnosis of AHU sensor faults (outdoor-air, mixed-air, and return-air temperature sensors)
- detection and diagnosis of AHU is not economizing when it should

- detection and diagnosis of AHU is economizing when it should not
- detection and diagnosis of AHU is using excess outdoor air
- detection and diagnosis of AHU is not providing sufficient ventilation air
- detection and diagnosis of low hot-water loop delta-T (difference between supply and return water temperatures)
- detection and diagnosis of constant hot-water loop supply temperature (no reset)
- detection and diagnosis of constant hot-water loop differential pressure (no reset)
- detection and diagnosis of high hot-water loop differential pressure set point
- detection and diagnosis of high hot-water supply temperature set point reset.

The first four algorithms include automated detection, diagnosis, reporting, and *correction*, while the remainders only involve automated detection, diagnosis, and reporting.

All of the algorithms are coded in the Python programming language and made compatible with the Transactional (VOLTTRON) Network[1] framework and the OpenEIS framework. The AIRCx process involves five basics steps:

1. Collect relevant data/information.
2. Detect the problem or re-tuning measure.
3. Diagnose the cause of the problem or re-tuning measure.
4. Report the problem to the operator.
5. Automatically correct the problem.

To collect data and to deploy the AIRCx part of the algorithms, the BACnet driver from the VOLTTRON agent execution platform is critical. This driver was developed as part of a separate project. It allows for two-way communication to BACnet compatible controllers and BASs.

Although the BACnet driver is essential for auto-correction, the detection and the diagnostics steps can be deployed using data collected from offline processes (i.e., comma-separated variable [CSV] text files) as well, and there are number of different ways these algorithms can be deployed. The algorithms are described in more detail in Katipamula et al. (2017).

[1] For information on the Transactional Network, see Haack JN, S Katipamula, BA Akyol, and RG Lutes. 2013. *VOLTTRON Lite: Integration Platform for the Transactional Network*. PNNL-22935, Pacific Northwest National Laboratory, Richland, WA.

7.0 University Project Team Accomplishments

The other members of the Clean Energy and Transactive Campus project team are University of Washington (UW) and Washington State University (WSU). UW installed multiple smart inverters to control power production from campus solar panels, and eventually will feed campus-produced photovoltaic power into the power grid. UW also usedits data analytics expertise to develop strategies to make buildings responsive to transactive control signals. WSU installed photovoltaic modules on campus for the first time and integrated them with Pullman's "Smart City" test bed and WSU's microgrid system. WSU also developed strategies for sharing energy between WSU's smart buildings and the solar modules.

This section summarizes the work conducted by UW and WSU.

7.1 University of Washington

UW connected smart inverters to PV panels installed by the University at multiple sites on the campus. It leveraged its expertise in data analytics to develop tools to analyze the data collected from these panels as well as from the instrumented buildings on the PNNL campus. It used its expertise in control to help PNNL develop control strategies for making buildings responsive to transactive control signals. Finally, it developed techniques and tools to optimize the operation of the battery in conjunction with the campus electrical load, the production of the PV panels, and transactive control signals. Originally, UW was also going to add a lithium-ion based BESS to be connected to the campus electrical distribution system; however, procurement issues hampered this part of the plan, and UW ultimately decided not to proceed with the BESS installation.

The following summarizes UW's accomplishments:

- Implemented the architecture to control the BESS in the VOLTTRON environment. An emulated BESS is being used to simulate the optimization framework. Simulations show that the BESS can shave power peaks of the UW's Electrical Engineering Building, as well as to respond to positive or negative transactive signals.
- Implemented the architecture to control the PV generation in VOLTTRON. Prior to installation of the PV equipped with smart inverters, agents that emulate the power production from these devices based on weather variables (cloud cover and temperature) have been implemented. The proposed algorithm iterates until it finds the optimal settings for the power factor input of the smart inverters, based on the current operating conditions and weather parameters.
- Completed a model to control the HVAC in using transactive signals in a multi-period framework. The model optimizes over a multi-objective function where the weights can be adjusted to favor cost minimization, enforcing comfort constraints or maximizing HVAC flexibility.
- Installed and commissioned solar panels (totaling 100 kW) and micro-inverters. PV generation is operational.
- Established secure link communication with the meters and the smart inverters in order to control them from the control center, in conjunction with UW's Clean Energy Institute and part of the Clean Energy Testbeds.

7.2 Washington State University

WSU invested in linking its new control center testbed with an energy management system and distribution management system through its Smart Cities initiative, which leverages Avista and WSU investments in the WSU microgrid and Pullman (WA) distribution infrastructures. The project at WSU installed new solar energy devices within the Pullman smart city footprint, as well as tools for planning, operation, and control of resilient distribution systems, transactive dispatch, and consumer engagement.

The following summarizes WSU's accomplishments:

- Conducted research on different auction mechanisms that enable transactive campuses.
- Integrated VOLTTRON with EnergyPlus to help simulate building loads that can be used to evaluate transactive agents.
- Designed and built a laboratory-scaled granular multilevel converter (GMC), which was then tested with different loads and operating conditions using OPAL-RT technology as the controller.
- Designed and built a laboratory-scaled PV inverter. The modified model predictive control (MPC) was tested by several experimental case studies in both steady state and dynamic conditions. The OPAL-RT technology was used to control the PV inverter.
- Completed a 72-kW solar array installation on the WSU campus.
- Completed the development of VOLTTRON agents to communicate with the WSU PV array, and completed and tested the network connection between the PV array and the testbed VOLTTRON devices.
- Integrated the PV telemetry data into the distribution management system (DMS) within the Smart City Testbed. Finalized the plan with WSU facilities to implement an on-campus test of the transactive scheme.

8.0 Subject Inventions and Software

As part of this project, the following invention disclosure was filed:

- Intelligent Load Control, IPID 31200. Open source copyright is pending DOE approval.

9.0 CRADA Summary

As the trend for clean and renewable energy resources accelerates in the United States and abroad, there is growing demand for innovative yet practical utilization of these new types of energy resources in realistic, live operation. At the same time, the intermittency of renewable resources requires greatly increased flexibility from the grid, at both the short-term (~minutes) and medium-term (~hours) time scales. To avoid the need to maintain or build new fossil-fired power plants to supply this flexibility, smart grid approaches turn to distributed assets such as responsive building loads and distributed energy storage to supply much of the needed flexibility. Since these new resources are small in size and large in number, and are distributed across the system, there is a need for distributed control solutions to manage them reliably and efficiently. Among the leading candidates for such solutions is transactive energy management. This project demonstrates not only the technical feasibility but also business viability of such solutions. The technologies demonstrated by this project will be of interest to developers of software for grid control, buildings management, home automation, smart meters, electric vehicle charging services, as well as electric utilities.

In summary, this project had the following overall outcomes:

- Successfully tested energy management of campuses as a substantial resource of balancing services needed by the regional power grid to achieve higher renewable penetration (solar and wind).

- Advanced key technology for flexible loads needed to accommodate renewables, reduce fossil fuel consumption, and improve economic and energy efficiency.

The R&D activities that PNNL, UW, and WSU conducted are designed to contribute to meeting important strategic objectives of the DOE Office of Electricity Delivery and Energy Reliability (DOE-OE) and DOE-EERE. The project provided a R&D platform upon which PNNL, UW, and WSU can support this nascent research funding.

Both the DOE-OE and the DOE-EERE view transactive energy approaches as key to their development and deployment of advanced technology for integrating distributed energy resources of various types, including flexibility from building loads and energy storage, to provide grid services. Transactive approaches provide a level economic playing field for such resources, providing them an equal opportunity to provide grid services alongside traditional grid assets. The distributed, hierarchical nature of transactive approaches parallels that of the grid; therefore, compared to centralized optimization approaches, it is a more convenient, practical, and natural way to integrate distributed resources while respecting economic self-interests and privacy across the boundary between the grid and customer enterprises.

In addition, the project advanced the demonstrated capabilities of the VOLTTRON platform, upon which DOE-EERE has focused strategic investment as an integration platform for a broad range of its end-use technologies. VOLTTRON is a software platform, essentially an operating system designed to manage networks comprised of large numbers of agent-based applications. Analogous to the Android operating system for cell phones, it is intended to provide an open environment within which vendors can concentrate their creativity and technology investments on developing the applications for building and device controls, and building and grid energy services, rather than on constructing an environment to host them. VOLTTRON offers built-in, state-of-the-art cyber security for such networks, as well as a rapidly expanding number of support services that make writing new applications easier. It also serves as a focal point for information interoperability, both within buildings and from buildings to grid, incorporating a growing number of protocols in its input/output capabilities. The project served to advance this agenda by demonstrating how VOLTTRON can be deployed at scale in a network comprising dozens of nodes, developing and testing new applications that will be implemented in the environment it provides.

As part of this project, the following publications were generated.

- Papers
  - Katipamula S, J Haack, G Hernandez, B Akyol and J Hagerman. December 2016. "VOLTTRON: An Open-Source Software Platform of the Future." *IEEE Electrification Magazine* 4 (4): 15-22. doi: 10.1109/MELE.2016.2614178
  - Kim W and S Katipamula. 2017. "Development and Validation of an Intelligent Load Control Algorithm." *Energy and Buildings* 135: 62-73.
  - Katipamula S, RG Lutes, G Hernandez, JN Haack, and BA Akyol. 2016. "Transactional Network: Improving Efficiency and Enabling Grid Services for Building." *Science and Technology for the Built Environment* 22(6): 643-654. doi:10.1080/23744731.2016.1171628
  - Katipamula S, K Gowri, and G Hernandez. 2016. "An Open-source automated continuous condition-based maintenance platform for commercial buildings." *Science and Technology for the Built Environment* 00, 1–11. doi: 10.1080/23744731.2016.1218236
  - Hao H, Corbin, CD, K Kalsi, and RG Pratt. January 2017. "Transactive Control of Commercial Buildings for Demand Response." *IEEE Transactions on Power Systems* 32(1): 774–783.
  - Corbin CD, S Katipamula, and D Vrabie. 2017. "Co-Simulation and Validation of Advanced Building Controls with VOLTTRON™ and EnergyPlus™." In *Building Simulation 2017*, San Francisco, CA.
- Reports
  - Kim W, S Katipamula, RG Lutes, and RM Underhill. 2016. *Behind the Meter Grid Services: Intelligent Load Control*. PNNL-26034, Richland, WA.
  - Hao H, G Liu, S Huang, and S Katipamula. 2016. *Coordination and Control of Flexible Building Loads for Renewable Integration; Demonstrations using VOLTTRON*. PNNL-26082, Pacific Northwest National Laboratory, Richland, WA.
  - Corbin CD, A Makhmalbaf, G Liu, S Huang, VV Mendon, M Zhao, S Somasundaram, H Ngo, and S Katipamula. 2016. *Transactive Control of Commercial Building HVAC Systems*. PNNL-26083, Pacific Northwest National Laboratory, Richland, WA.
- Presentations
  - 2017 IEEE PES General Meeting, Chicago, IL. July 18, 2017. "VOLTTRON™ MAS Platform for Buildings Flexibility and Other DER Integration." Srinivas Katipamula, Presenter.
  - 2017 Energy Summit – Power and Energy Automation Conference, Spokane, WA. March 23, 2017. "Clean Energy and Transactive Campus (CETC) Project: Phase I." Srinivas Katipamula, Presenter. PNNL-SA-124970.

10.0 References

Corbin, CD, A Makhmalbaf, S Huang, VV Mendon, M Zhao, S Somasundaram, G Liu, H Ngo, and S Katipamula. 2016. *Transactive Control of Commercial Building HVAC Systems*. PNNL-26083, Pacific Northwest National Laboratory, Richland, WA.

Hao, H, G Liu, S Huang, and S Katipamula. 2016. *Coordination and Control of Flexible Building Loads for Renewable Integration*. PNNL-26082, Pacific Northwest National Laboratory.

Katipamula, S, RG Lutes, RM Underhill, and S Huang. 2017. *Automatic Identification of Retro-Commissioning Measures*. PNNL-XXXXX, Pacific Northwest National Laboratory, Richland, WA.

Kim, W, S Katipamula, RG Lutes, and RM Underhill. 2016. *Behind the Meter Grid Services: Intelligent Load Control*. PNNL-26034, Pacific Northwest National Laboratory, Richland, WA.

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