

Implementing An Eclipse Volttron-based Software Platform to Make a Building “Grid-Interactive”

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ABSTRACT

A Grid-interactive Efficient Building (GEB) is not only energy efficient but can also shed building load during peak hours, or shift demand to use cheaper or cleaner power. Most of the existing building automation systems (BAS), however, cannot integrate with different Distributed Energy Resources (DER), directly communicate with utilities' automated demand response (ADR) signals, or implement complex algorithms optimizing all DERs to maximize benefits. Our team implemented an Eclipse VOLTTRON-based software platform to transform a typical office building into a GEB building. The key components of this platform include an edge device (small computer) connected to the BAS network for integration, communication, optimization, and control, a computer server with database software to store historical trend data, and another computer server running Grafana - a cloud-based dashboard software - as the user interface. One of the key features of this GEB control platform solution is that the platform components are "open source" and free-to-use. This paper describes our experience and lessons learned implementing the GEB control platform and developing load-shedding, load-shifting, and continuous load management algorithms from a typical controls contractor's perspective.

Introduction to GEBs

Based on the U.S. Department of Energy (DOE 2020), Grid-interactive efficient buildings (GEBs) are “energy-efficient buildings with smart technologies characterized by the active use of distributed energy resources (DERs) to optimize energy use for grid services, occupant needs and preferences, and cost reductions in a continuous and integrated way.” GEBs will play an important role in the transition to a decarbonized economy, as buildings account for more than 70% of U.S. electricity use and at least one-third of U.S. economy-wide CO₂ emissions, and GEBs can provide valuable grid services to the future smart grid.

Key components of a GEB include behind-the-meter DERs: Heating, Ventilating, and Air-conditioning (HVAC) equipment; plug loads; lighting system; thermal and battery energy storage; managed electric vehicle (EV) charging; solar photovoltaic (PV); wind turbine, local emergency generator, combined heat and power, fuel cells, and other technologies. There are four attributes or characteristics of a GEB:

- *Efficient:* GEBs are efficiently run buildings that are free of equipment and operational faults while maintaining the building functions and occupant comfort.
- *Connected:* GEBs enable two-way communication between technologies, the grid, and occupants and can respond to time-dependent grid needs.

- *Smart*: GEBs support advanced, optimal controls for buildings and community energy systems.
- *Flexible*: GEBs can provide dynamic load control to support the electric grid, including shedding, shifting, and modulating loads

GEBs can provide different grid services to the future smart grid through energy efficiency, load shedding, shifting, modulation, and generation. This can be done by *integrating* these behind-the-meter DERs, *communicating* with utilities, and *optimally controlling* these DER to maximize the benefits to both the building owners and the utilities while minimizing the occupant comfort impact. For building owners, GEBs can bring in value streams by taking advantage of utilities' demand response incentive programs. For utilities, GEBs can help balance power supply and demand and reduce the need to build more power plants.

Introduction to GEB Control Platform

A GEB requires a flexible GEB control platform that can *integrate* with different DERs, *communicate* with utilities' ADR signals, and execute very complex *optimal control* algorithms. Figure 1 illustrates a generalized GEB control platform for a single building. The dotted line represents the building boundary. The major building energy equipment and behind-the-meter DERs are represented by icons for HVAC, lighting, plug loads, PV, storage, and EV charging. The optimization and control function happens in the edge computing device installed on-premises, as illustrated in Figure 1. However, this function can also be executed in the cloud.

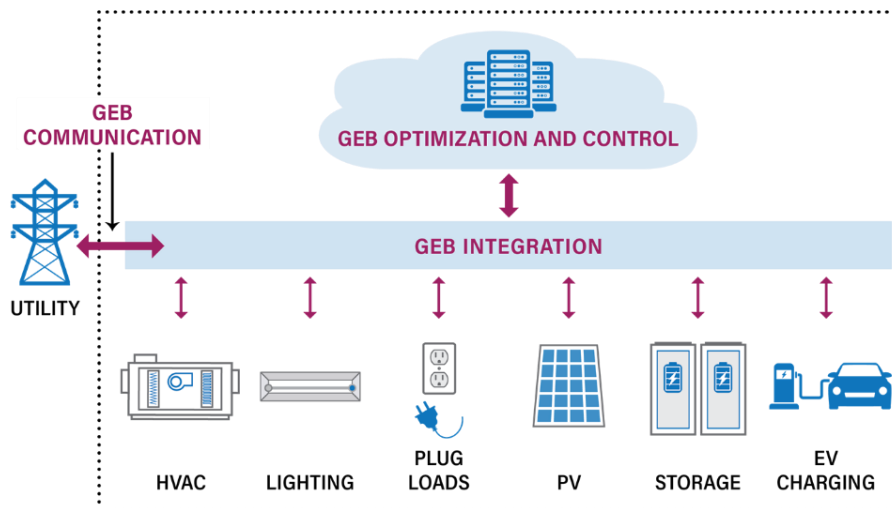


Figure 1. An Illustration of a General GEB Control Platform.

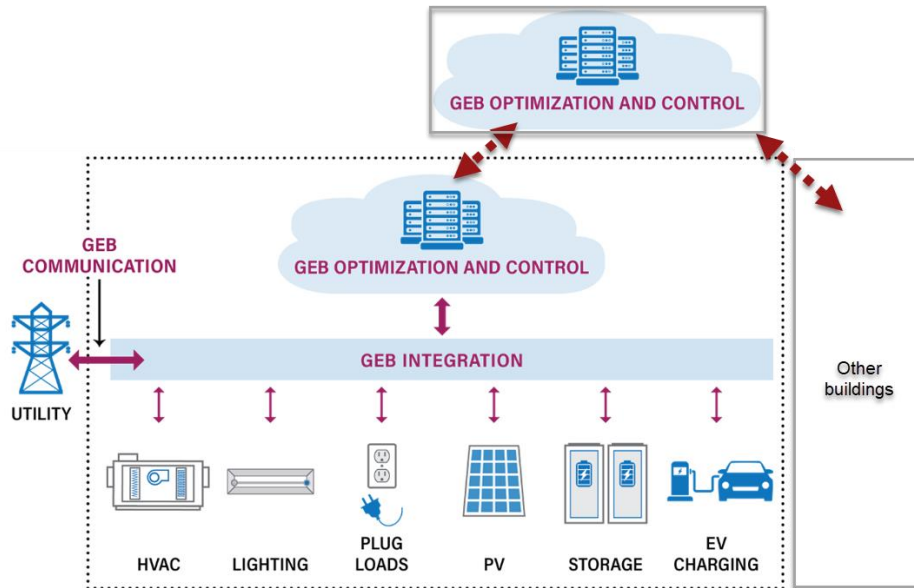


Figure 2. An Illustration of a General GEB Control Platform for Multiple Buildings.

Figure 2 shows a GEB control platform that can coordinate GEB activities among multiple buildings. Besides the GEB integration and GEB optimization and control within each participating building at the building level, a higher-level GEBs coordination is needed. This coordination/optimization and control usually is cloud-based.

A GEB control platform consists of three main technology areas:

Integration

The GEB control platform needs to integrate multiple DERs to optimize and control them as a system. For example, modern HVAC control systems are mostly using open protocols such as BACnet or LonTalk, but the lighting control industry has not standardized the digital communication protocols for networked lighting controls. Energy storage systems, managed EV charging, and solar PV inverters all have their control software and communication standards. Therefore, the GEB control platform needs to be able to exchange information with all these DER control systems or software, which is a huge challenge.

Communication

While integrating multiple DERs into the GEB control platform involves two-way communications between the DER control software and the platform, the communication here is specifically referring to the GEB control platform communication with the utilities. For GEBs to provide grid service, the GEB control platform needs to know when the grid needs buildings to shed, shift, and modulate building load, and by how much. GEBs also need to know the electricity rate structure. The actual building power data will be sent back to utilities for verification of building load reduction. The communication between utilities and GEBs is also

two-way communication. The most popular ADR communication standard is OpenADR (OpenADR Alliance 2022 a) by OpenADR Alliance (OpenADR Alliance 2022 b.)

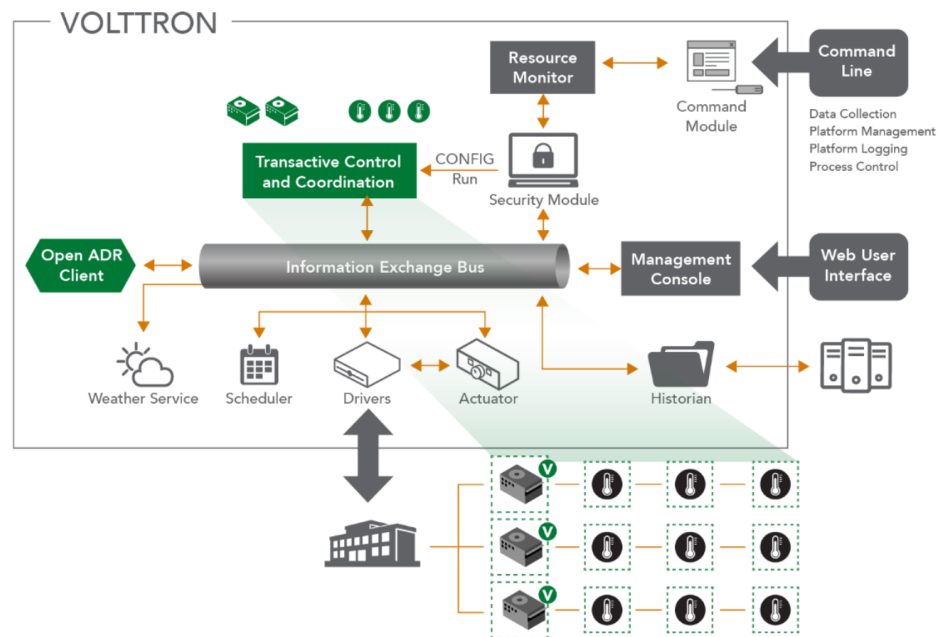
Optimization and control

The “brain” of the GEB control platform is its optimization and control algorithm. The algorithm needs to be based on all available information: controllable variables such as HVAC system setpoints, networked lighting system dimming level setpoints, plug load controller on/off, local generation on/off, battery storage charge/discharge times, EV charging enable/disable and rates, etc.; observable variables such as electrical power at individual equipment or circuits and space temperatures and light levels, etc.; current weather condition and weather forecast; and constraints such as predetermined occupant thermal and visual comfort ranges. Then it will make the best decisions to achieve the maximum benefits – i.e., the highest utility incentive amount, deepest peak demand reduction, largest Greenhouse Gas (GHG) emission reduction, or a combination of these objectives. The optimal or near-optimal control decisions can be obtained by forming and solving complex mathematical multi-objective optimization problems based on available information, constraints, and objectives. On the other hand, utilities can design or adjust their incentive rate structures and automated demand response events to control their grid service needs.

Eclipse VOLTTRON

Originally developed by Pacific Northeast National Laboratory, Eclipse VOLTTRON (Hernandez 2018) is a Linux-based “open-source distributed control and sensing platform for connecting devices, managing data, and executing actions.” As illustrated in Figure 3, VOLTTRON has all the key functions that can be used in a GEB control platform. It was designed for the new *Transactive Energy* concept, which refers to the “combination of economic and control techniques to improve grid reliability and efficiency” (Katipamula 2017). The information exchange bus can be used to exchange information among different building energy system components as well as utility automated demand response (ADR) signals. VOLTTRON “provides an agent-based programming paradigm to ease application development and minimize the lines of code that need to be written by domain experts (such as building engineers).” Agent-based programming is a programming paradigm where the construction of the software is based on the concept of software agents, which have interfaces and messaging capabilities. VOLTTRON V-agents – codes written in Python – can be used to run very complicated optimization and control algorithms for optimally controlling building DERs to achieve maximum benefits. VOLTTRON integrates with various building energy systems through

software drivers. For BAS integrations, the VOLTTRON BACnet driver¹ is available.



Source: Pacific Northwest National Laboratory

Figure 3. An Illustration of the VOLTTRON Architecture. Source: PNNL.

Test Building and Building Energy Systems

Slipstream has been very interested in exploring and testing various GEB control platform solutions in the past several years. Several commercial Energy Management and Information System (EMIS) software companies have added the GEB integration, communication, and control capabilities on top of their existing software that was focused on building energy efficiency, energy monitoring, analysis and management, fault detection and diagnosis, and building operations optimization. Their software architectures fit in the general GEB control platform architecture described previously. However, they often use proprietary, software drivers, communication protocols, and optimization and control algorithms. Slipstream has been partnering with two of them to demonstrate GEB controls in the GSA Green Proving Ground (GPG) and the DOE High Impact Technology (HIT) Catalyst programs.

Starting in 2020, we have worked with Ace IoT Solutions, a software development company that provides technical solutions for Eclipse VOLTTRON-based system, to design and implement a GEB control platform in the Slipstream headquarter office in Madison, WI.

The Slipstream headquarter office (Figure 4) Figure 4. Slipstream Headquarters Office Building is an approximately 34,250 square feet, two-floor office building. It is comprised mainly of open and private office spaces, with two large training rooms and several conference rooms,

¹ <https://volttron.readthedocs.io/en/latest/driver-framework/bacnet/bacnet-driver.html>

and associated circulation spaces. It was built in 2008 to a LEED Gold standard. The building was designed with a maximum of 170 occupants on each of the two floors.



Figure 4. Slipstream Headquarters Office Building

Mechanical system

The test building is heated, cooled, and ventilated by a single DX/Gas-Fired VAV rooftop air handling unit (RTU). Thirty single-duct, variable air volume (VAV) terminal units throughout the building have hot water reheat coils served by a natural gas boiler system. The RTU is also served by an enthalpy plate energy recovery ventilation (ERV). The 21,000 cfm RTU has direct expansion (DX) refrigerant cooling and a gas-fired heat exchanger and a built-in air-cooled condenser unit with fans to reject heat from the refrigerant. The RTU has two supply fans - each with a variable frequency drive (VFD), one return fan with a VFD, and four DX compressors. The unit has a total nominal capacity of 60 tons of cooling. The ERV contains an exhaust fan and an outdoor air fan, each downstream of the heat exchanger in their respective airstreams. The ERV is ducted down below the roof and then back up into the RTU. Most thermostats are wall-mounted in the zones they serve. Local thermostat setpoints are overridden by the building automation system (BAS) temperature setpoints. The heating hot water system serves the air terminal reheat coils, radiant perimeter heat, and cabinet unit heaters throughout the building.

Building automation system

The BAS controlling the building consists of a Trane Tracer SC+ supervisory controller for supervisory control, Johnson Controls field equipment controllers (JCI 2018) and VMA controllers (JCI 2006) for VAV terminal units, unitary equipment, and boiler hot water system control, and a Niagara AX JACE controller (AAON 2022) for RTU and ERV control.

The existing field level controllers include (30) JCI VMA controllers (JCI 2006) serving temperature control (VAV's) in individual zones, (2) entryway cabinet unit heaters (CUH), boiler hot water system (Trane UC600), and roof-mounted air handling unit. The Trane Tracer SC+ controller is a fully native BACnet[®] system and provides a web-based user interface. The Trane controller also stores a limited amount of BAS trend data. Any computers on the

building's internal TCP/IP LAN will have access to the BAS user interface as the LAN is not segmented as a separate virtual LAN (VLAN) dedicated for building automation purposes.

The RTU controller is factory-packaged and programmed. The hardware includes JENEsys branded Niagara AX JACE controller which is integrated BACnet/IP Trane SC through the LAN. The controller is also not completely customizable as access to the logic that controls the rooftop inside the JACE is considered proprietary and locked out by the manufacturer. However, the Trane Tracer SC controller has supervisory control logic implemented related to mechanical cooling, economizer cooling, enthalpy calculations, fan control, gas heating control, and space temperature sensor averaging.

There are over 800 monitoring and control points in the building BAS. The most important BAS points were integrated into the Slipstream GEB control platform through BACnet®. These BAS points were trended in the GEB database at 1-minute intervals and can be presented through the Grafana dashboard specifically set up and configured for the Slipstream GEB control platform.

Electrical system

There are approximately 465 circuits in this building. All circuits have been categorized as one of four types: lighting, plug load, HVAC, and other/empty. eGauge power and energy meters are installed to measure and collect energy use data on some of these circuits. These eGauges have built-in web servers, and the circuit-level power data were configured as BACnet objects and were integrated into the Slipstream GEB control platform for monitoring and trending.

Photovoltaic (PV) system

The building has a 19-kW solar PV system in four arrays. The system generates roughly 65 kWh on an average day. This 19-kW peak power generated by the PV system represents about 20% of building demand on a very hot summer day and roughly 50% of building demand on a normal day. The table below summarizes the quantity and power of modules in each array. The original system (commissioned with the building in 2007) consisted of six Magnetek inverters. Later they were changed to three Fronius Primo 5 and Primo 6 model inverters. Documentation for the Fronius Primo inverters indicates that they include the Fronius Data Manager 2.0, with the following interfaces (Table 1):

Table 1. Solar PV Inverter Interfaces

Ethernet (RJ45 socket)	LAN 10/100, Fronius Solar.web, Modbus TCP SunSpec, Fronius Solar API
WLAN	Wireless standard 802.11 b/g/n, Fronius Solar.web, Modbus TCP SunSpec, Fronius Solar API
6 digital inputs	Interface to ripple control receiver
4 digital inputs/outputs	Interface to ripple control receiver, load management
RS485	Modbus RTU SunSpec or meter connection

The Fronius Primo inverter includes Modbus registers allowing control of the following functions: the deactivation of inverter's grid power feed operation (standby), constant reduction of output power, specification of a constant power factor, and specification of a constant relative reactive power. The integration of the Fronius Primo inverter into our GEB platform was through the Modbus TCP protocol.

The Test GEB Control Platform Architecture

In 2020, we partnered with Ace IoT Solutions to design and implement a VOLTTRON-based GEB control platform at our Slipstream headquarters office building. We chose the VOLTTRON-based platform mainly because this is an open-source, distributed control and sensing platform, and open-source license terms and conditions apply.

The platform hardware mainly consists of a web application server, a database server, and a computer /edge device with VOLTTRON installed (Figure 5). The computer /edge device is also called the Eclipse VOLTTRON server. The web application server is installed with a Grafana server software - open-source analytics & monitoring solution from Grafana Labs. A couple of Slipstream researchers working remotely installed the VOLTTRON platform and a Python programming software locally on their laptops in order to develop high-level GEB control and monitoring algorithms and then deploy the algorithms on the VOLTTRON edge device. The VOLTTRON edge device is the primary device that integrates with the building energy systems and behind-the-meter Distributed Energy Resources (DERs), communicates with utility automated demand response (ADR) signals, and runs GEB monitoring and control algorithms. The various components of the platform within the Slipstream building boundary are physically connected through high-speed Ethernet cables. The two Slipstream researcher research environments that are outside the Slipstream building boundary are not on the same network as the GEB control platform, but they can communicate with the GEB platform through the internet either using HTTP or VOLTTRON ZMQ protocols. The ADR communication can be tested using either a Slipstream OpenADR Virtual Top Node (VTN) or a utility/third-party provided OpenADR VTN.

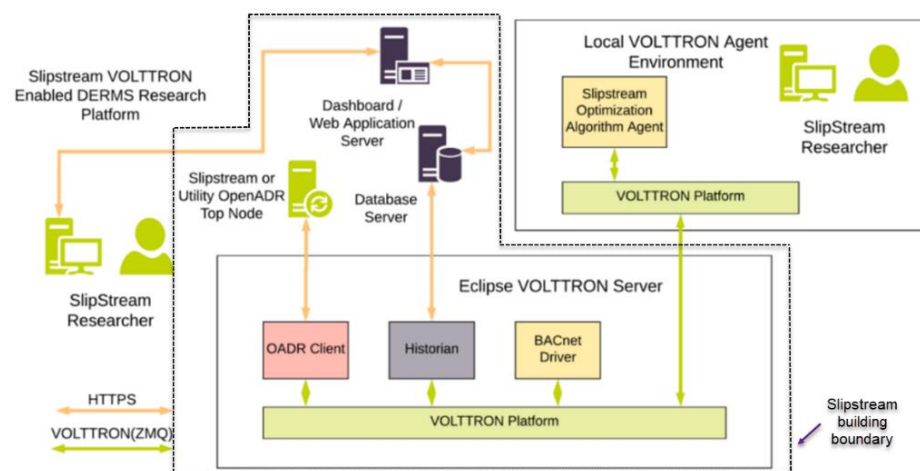


Figure 5. Slipstream GEB Control Test Platform Architecture

Integration

Our GEB test platform was integrated with 1) a building automation system, 2) eGauge power and energy meters, 3) a couple of BERT plug load controllers, and 4) three solar PV inverters. The integration used various network options and protocols – refer to Table 2. Sample photos of these components are shown in Figure 6.

Table 2. GEB Integration List

<i>System/DER</i>	<i>Integration Description</i>	<i>Protocol used</i>
Building Automation System	Trane Tracer SC+ supervisory controller through Ethernet network	BACnet
Plug Load Controller	Bert smart plug BERT 110 M using the existing 802.11 Wi-Fi networks through Bert's RESTful APIs	HTTPS
Circuit-level Power	eGauge power meters (EG-4015) through Ethernet network	BACnet
Solar PV	Fronius Primo inverters through Ethernet network	Modbus TCP

The integration provided one-way (eGauge) or two-way communications with the GEB components and can collect data from and/or send commands to these components.



Building Control System



eGauge Power Meter



BERT Smart Plug



Solar PV Inverter

Figure 6. Components Integrated with the Slipstream GEB Control Platform

Communication

The GEB platform's capability to communicate with utility's ADR signals and respond with controls to shed/shift building loads or provide other grid services in times of need is critical. We tested the platform's capability to receive and interpret OpenADR signals (Figure 7.) Open Automated Demand Response (OpenADR) provides a non-proprietary, open standard for DR and DER applications. This standard is used by many utilities in the U.S., especially in the west coast states. In our experiment, we used IPKey's² Virtual Top Node (VTN) to set up test events.

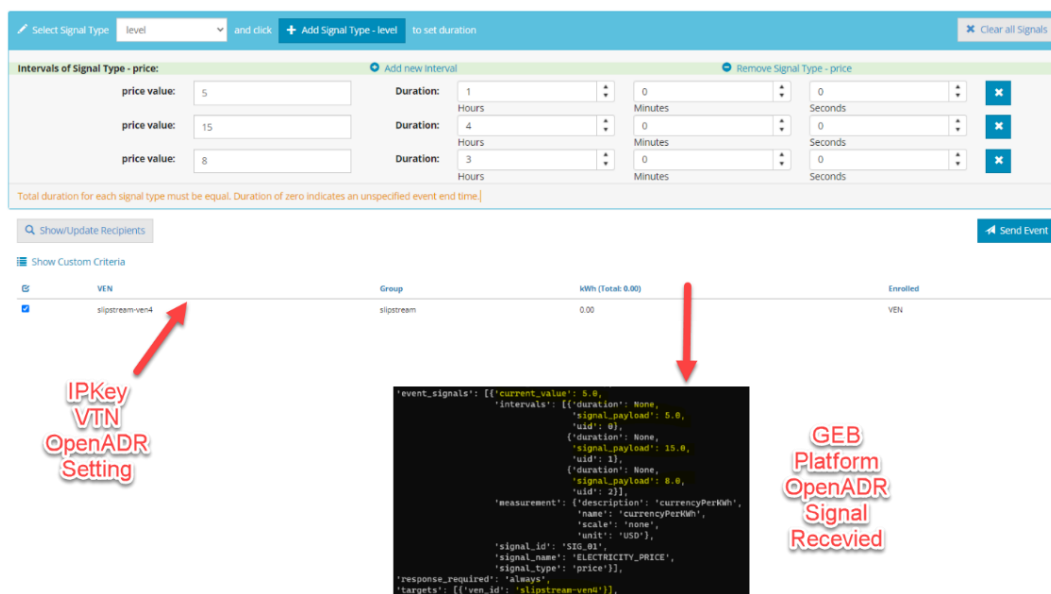


Figure 7. OpenADR Communication Testing

User Interface

Our GEB control platform uses the Grafana dashboard as the GEB system monitoring user interface. Grafana dashboard is “a set of one or more panels organized and arranged into one or more rows” that can be customized to fit customer needs (Grafana Labs 2022.) Each panel can interact with data from the database server, which stores data collected from the GEB components in this building (BAS monitoring and control points, circuit-level power, PV power generation, etc.) A screenshot of a dashboard example is shown in Figure 8.

² <https://ipkeypowerpartners.com/products/eiss-energy-interop-server-system/>

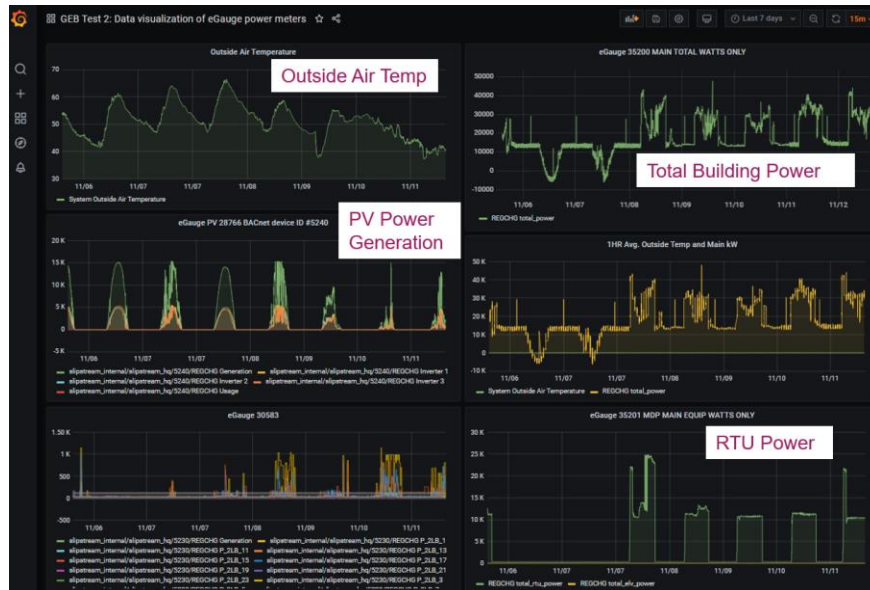


Figure 8. GEB Test Platform Dashboard

Load Shedding, Load Shifting, and Continuous Load Management Tests

Common demand respond (DR) strategies for RTU + VAV terminal units include zone temperature setpoint reset or directly controlling RTU compressor on/off or speed. For load-shedding tests, mostly we increased all zone cooling temperature setpoints by +2 Deg F at a specific time of day or based on simulated ADR event signals. For load shifting, we pre-cool the building early in the morning to lower-than-normal zone temperature setpoints, then graduate increase the setpoints throughout the day. For continuous load management, a specific building load limit and the PV power generation were constantly monitored in real-time throughout the day. When the building load approached the load limit, all zone cooling temperature setpoints were increased by +2 Deg F so the RTU compressor would not go to another stage. These control strategies were programmed using Python and run on the Eclipse VOTTRON edge device. The baseline 24-hour load profiles were established utilizing the proxy day methods - averaging the highest three days' load in the 10 days before the test day. This baseline method selection is based on the method used by several utility demand response programs. The test day load profile compared to the baseline profile for the load shedding test is illustrated in Figure 9. During the experiments, we did not conduct occupant comfort surveys due to limited staff working in the office because of Covid.

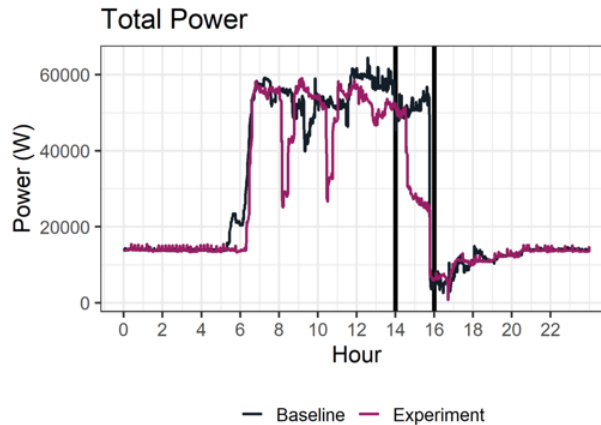


Figure 9. Load Shedding Test Day Load Profiles Compared to Baseline

Table 3. Load Shed Test Result

Metric	Total Building Power
Average demand shed	16,477 W
Average demand shed intensity	0.48 W/sf
Average percent reduction during event hours	31%

Lessons Learned

It took a significant amount of time to learn how to set up and configure the VOLTTRON-based GEB control platform because it is not anything like a traditional building control system platform. Slipstream engineers had to learn about VOLTTRON, python, basic Linux commands, and develop, run, and debug VOLTTRON “agents” – python programming for the load shedding, load shifting, and continuous load management algorithms. The GEB control platform infrastructure also needs routine monitoring and maintenance by IT staff and VOLTTRON experts.

Because VOLTTRON is an open-source platform, the integration and communication with various distributed energy resources (DERs) depend heavily on the VOLTTRON drivers developed and supported by the VOLTTRON community including Pacific Northwest National Laboratory. A VOLTTRON driver acts as an interface between “agents” on the VOLTTRON platform and a device. In our experiments, the VOLTTRON Open ADR driver we initially tested was not fully compatible with standard OpenADR 2.0a and b profile specifications, and we have to wait for the VOLTTRON community to develop a new version before we can test the OpenADR communication again.

We also learned that to effectively shed or shift building loads through BAS, the faults within the HVAC equipment and controls need to be identified and eliminated first. Without an efficiently run HVAC system, it is difficult to effectively shed or shift the HVAC load. No additional BAS software needed to be added in our GEB testing and no VOLTTRON involved in

fixing these faults. However, our team had to work with the local controls contractor to change the existing building control sequences such as economizer and RTU compressor control logic, as well as change the narrow two-degree deadband between VAV zone heating and cooling setpoints to five degrees.

Future Work

Overall, we like the VOLTTRON-based GEB control platform because of its openness, and it has the features needed to implement GEB functions: integration with various devices, communication with utilities ADR signals, and can implement complex control and optimization algorithms. The platform does need special skills to maintain, integrate with various GEB components, and develop and run complex monitoring and control algorithms. Our future work includes integrating other types of GEB components – connected lighting systems, managed EV charging, and battery storage, conducting more experimental tests for deeper load flexibility and developing and testing more advanced GEB control algorithms. We are currently working with PNNL and other partners in addressing various challenges in commercializing and scaling up the VOLTTRON-based GEB control solutions.

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