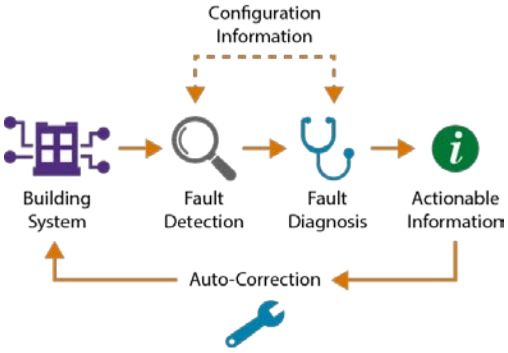
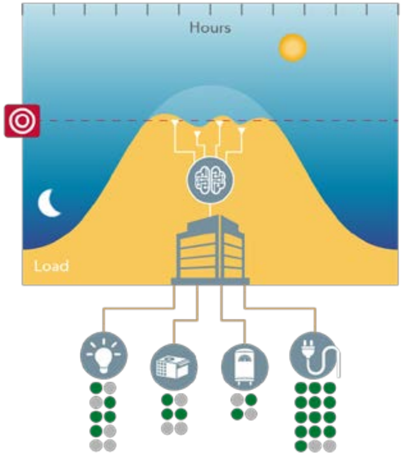
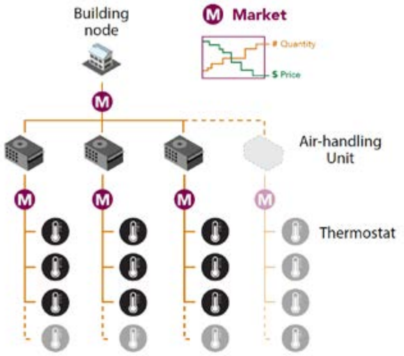
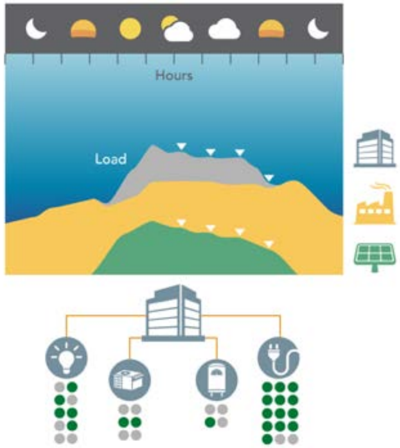
Transactive Signal Methodologies: Clean Energy and Transactive Campus (CETC) Project









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Project Summary

Timeline:

Start date: January 2016

Planned end date: March 2019

Key Milestones

1. Design, develop and deploy infrastructure to support multi-campus experiments complete; 5/30/2017
2. Multi-campus integration and testing complete; 9/30/2017
3. Complete development and testing of algorithms that provide transactive control services complete; 12/31/2018

Budget:

Total Project $ to Date:

- DOE: $5.2M
- Cost Share: $5.275M

Total Project $:

- DOE: $5.7M
- Cost Share: $5.775M

Key Partners:

Washington State University (WSU)
University of Washington (UW)
Case Western Reserve University (CWRU)
University of Toledo (U-Toledo)

Project Outcome:

- Design, develop and test scalable technologies that advance commercial building energy efficiency and transactive control of distributed energy resources (DERs)
- Create a “recipe for replication” of transactive controls for buildings, campuses and districts, as utilities, municipalities, and building owners are facing larger deployments of clean energy technologies and aging infrastructure
- Establish a clean energy and responsive building load research and development infrastructure in Washington State
- Contribute to Building Technologies Office, Grid Modernization Laboratory Consortium and Grid Modernization Initiative goals

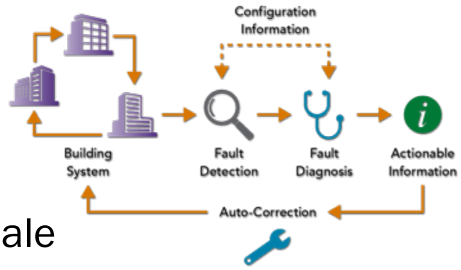
Team

- **PNNL**: Lead, coordinate work done by WSU, UW, CWRU, U-Toledo and PNNL
  - Designed and deployed VOLTTRON™ network infrastructure on PNNL campus, including the ability to integrate with WSU, UW, CWRU and U-Toledo
  - Designed, developed, implemented and tested energy efficiency (EE) and grid service (GS) experiments on PNNL campus testbed
  - Development of simulation testbed to test grid service technologies and development of transactive energy simulation testbed for studying distribution network
- **WSU**: Explore transactive micro-grid concepts
  - Procured 72 kW solar photovoltaic (PV) with smart inverters
  - Explore transactive energy scenarios on the WSU campus utilizing the existing energy resources and transactive controls, including the 72 kW solar array, Smart City Testbed's distribution management system, VOLTTRON nodes, and WSU's facilities
- **UW:** Explore transactive energy concepts
  - Procured smart inverters for existing solar PV panels and conducted experiments to mitigate solar imbalance with a battery energy storage system (BESS) and flexible loads
- **CWRU:** Test PNNL-developed energy efficiency and GS technologies
- **U-Toledo**: Test PNNL-developed GS technologies with a transactive network system

Challenge

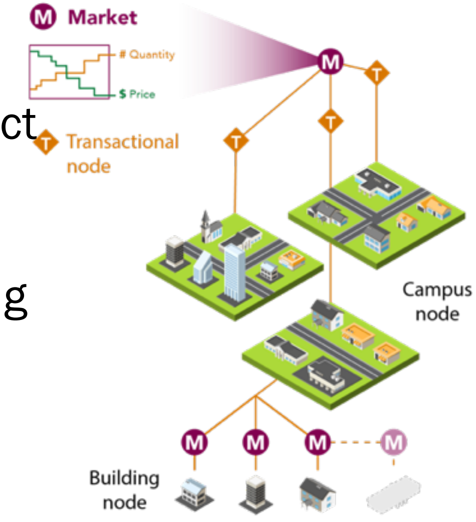
EE

- Today, buildings use as much as 30% more energy than required
- Only 14% (43% of conditioned space) of the building stock has building automation systems (BAS)
- Automated fault detection and diagnostics (AFDD) and automated identification of retro-commissioning (AIRCx) measures can reduce energy consumption and cost
  - AFDD technologies exist, but have not been proven on a large scale
  - AIRCx technologies do not exist, it is still a manual process



GS

- With increasing penetration of distributed renewable generation, traditional approaches of supporting grid reliability can be expensive
- Managing controllable flexible loads in buildings can reduce peak by up to 20% for short duration without significant impact to service levels
- Transactive control (TC) provides a viable solution for coordinating responsive building loads and DERs for improving grid reliability
  - Must be tested in realistic situations
  - Must develop approaches that enable a single building, sets of buildings, or entire communities to readily adopt them



Current State of Building-Grid Integration

- Lack of ability to transact energy-related services with other buildings or entities (other than the independent system operator/utility) impedes financial motivation to engage robustly with distributed renewable energy (RE) and storage
- Lack of scalable methodologies that are relevant to current markets but also future markets
- Past approaches tested services on individual buildings, and it was clear that to develop scalable solutions more tests are needed
- Scalable solutions – one off custom solutions are not cost-effective
    - Automation, turnkey, open source, flexible and interoperability are key for scalability
    - Building owners/occupants in full control – ability to override

Opportunity for Buildings

- Buildings have a large role in helping to enhance grid reliability and enabling the rapid integration of RE and storage

BUT

- Buildings today are limited by existing controls systems that cannot easily transact at a scale that is required by the grid
  - High cost to "get it right" with existing technology and economics
  - Currently only implemented in large buildings
  - Components are emerging with greater capabilities
- Building solutions must "think across the meter"
  - EE is at the core, but there are additional value streams to/from third party entrepreneurs
  - Better control of loads have other benefits
- Thinking differently will unlock new value streams…
- **Multiple value streams**
  - Spreading the cost of technology and ongoing operations
  - Grid **or** EE services alone may not be sufficient
  - Simultaneous deployment of **both** grid and EE services

Project Objectives, Goals and Outcome

- **Objective** is to form a multi-campus network (PNNL, WSU, UW, CWRU and U-Toledo) and conduct research and development that advances commercial building EE and transactive control of DERs
- **Key goals** of the research include developing technologies that would allow achieving significant energy savings in large numbers of commercial buildings; and allow integration of renewables at both local and regional scale without impacting grid reliability by using transactive control to coordinate large numbers of DERs
  - DERs include flexible building loads, energy storage systems, smart inverters for PV and battery systems, and electric vehicles
- **Key outcome** is to create a "recipe for replication" of transactive control and coordination for buildings, campuses and districts, and utilities, municipalities, and building owners are facing larger deployments of clean energy technologies and aging infrastructure
  - Reference designs – market designs and behind-the-meter grid and efficiency delivery technologies

Approach

2016

Focus is on behind-the-meter technologies and individual buildings

Identify technologies needed to improve EE and grid reliability

Develop or adapt technologies and integrate them with VOLTTRON

Start experiments, first in simulation environment and then in real buildings

Partners acquire smart grid testbed assets

2017

Focus is on behind-the-meter technologies and individual buildings

Experiment EE service and GSs in individual buildings

Document technologies

Enhance technologies

Add two more partners

2018

Focus is on both sides of the meter and multiple buildings with transactive market system

Add additional smart grid assets

Continue EE services

Develop transactive market system

Coordinate GS experiments in multiple buildings & City of Richland

Enhance modeling approaches using machine learning techniques

Extend experiments using partner assets

Approach (future)

2019

Focus is on both sides of meter, validation of “recipes of replication” at distribution scale, work with utility and other partners

Develop additional market systems that integrate supply and demand curves

Extend experiments to multiple buildings on multiple campuses

Develop multiple time step price-capacity curves for end uses

Continue improvements in load forecasting, price-capacity curves and advanced and transactive controls using machine learning

Develop a validation plan to test “recipes of replication” and identify utility/other partners that will support the validation effort

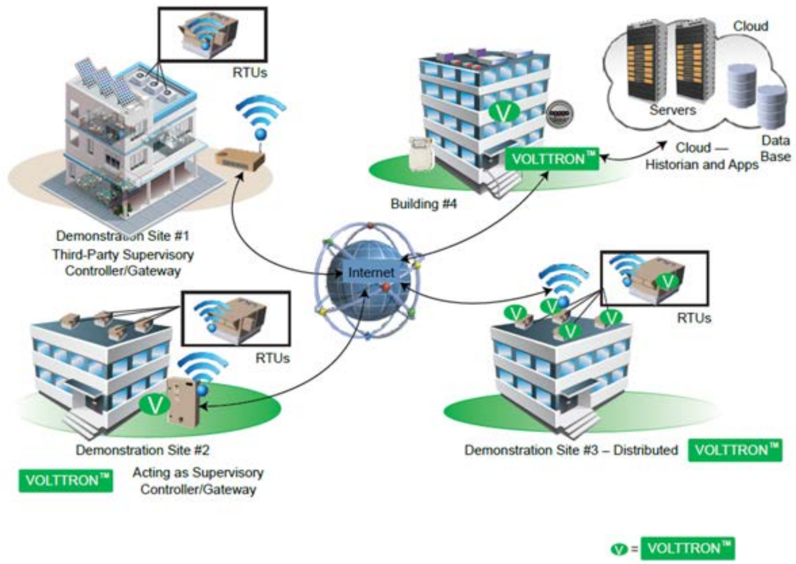
2020

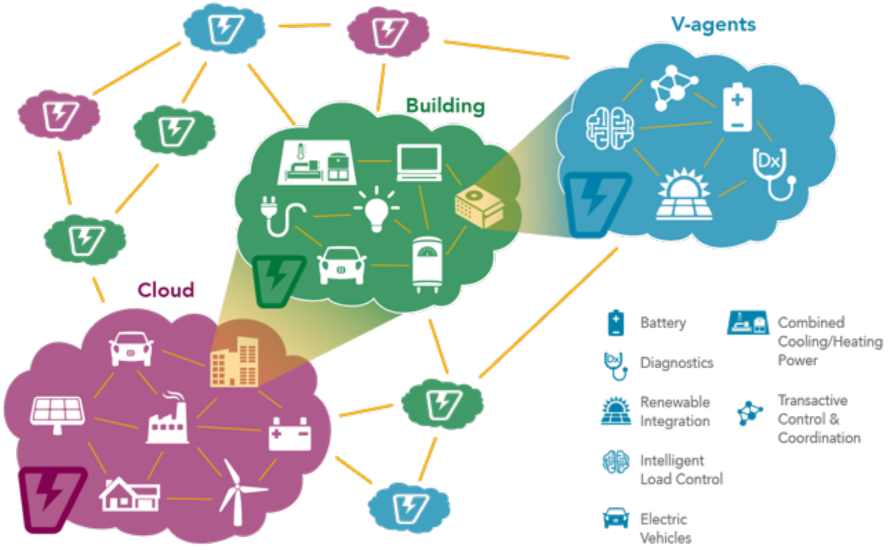
Focus is on both sides of meter, validation of “recipes of replication” at distribution scale, work with utility and other partners

Validate “recipes of replication” in the field (work with Commercial Building Integration)

Approach: Key Issues

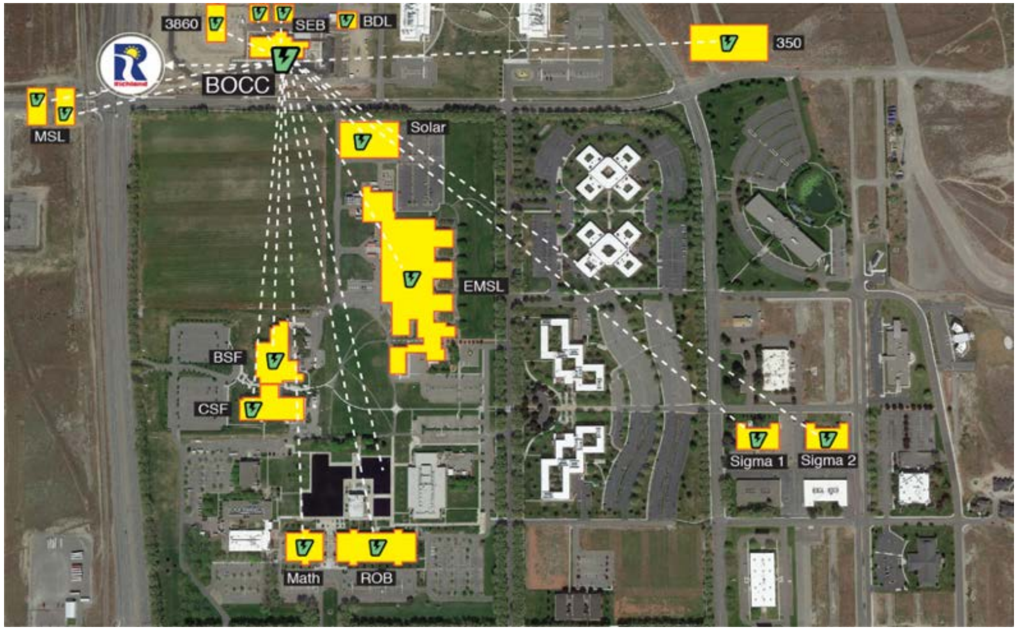
- Develop and demonstrate EE and transactive control technologies that improve building performance, better manage building electric loads, increase hosting capacity of RE, enhance grid operations, reduce cost and increase EE
- Create methods that enable these approaches to be readily adopted and implemented in single or sets of buildings, and communities at scale





Approach: Distinctive Characteristics

- First **behind-the-meter** implementation of transactive energy at this **scale**, involving multiple buildings and devices
- Innovative DOE-supported, PNNL-developed **VOLTTRON, distributed control and sensing** platform, provides a foundational tool for supporting individual experiments and connecting the partners' research activities
  - VOLTTRON deploys "agents" (algorithms) in building and other systems to coordinate various actions
- Technology can be launched from **inexpensive computing** devices



Experiment deployment on the PNNL campus

Impact: Target Market and Audience

- **Contribute to the BTO goals**
  - Reduce existing commercial building energy consumption by 30% by 2030
- Target market = commercial
- Total primary energy consumption of commercial buildings is approximately 18 Quads
- **Potential energy savings = 4 to 5 Quads**
- **Potential cost savings of several billion dollars annually in reduced energy costs with just 10% peak reductions**
- **Support GMLC/GMI crosscutting goals**
- **Target Audience:** Utilities, energy service providers and any campus considering deploying EE and transactive energy services

Impact of Project

- Project will provide tools that enable the commercial buildings sector to replicate the project's technology implementations and methods, leading to **improved EE**, **increased integration of renewable energy, and enhanced power grid reliability**
- **Outcomes of the project include**:
  - **Short-term (immediate)**: Development, validation, and release of open source EE and transactive control software tools compatible with VOLTTRON; associated technical documentation and user guides that will comprise the "recipe" and enable replication
  - **Medium-term (<3 years)**: Two or more energy service providers deploying the software tools to benefit buildings and the grid
  - **Long-term (>3 years):** One or more utilities deploying transactive energy concepts at a distribution scale

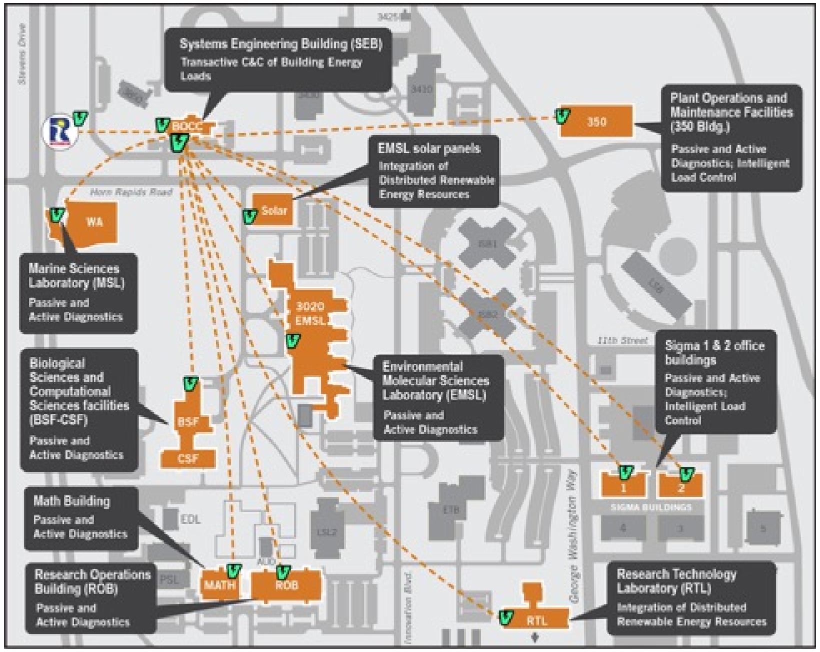
Progress 2016: Technology Development and VOLTTRON Deployment

Focus is on Behind-the-Meter Technologies and Individual Buildings

- Developed/adapted technologies
  - Automated Fault Detection and Diagnostics (AFDD)
  - Automated Identification of Retro-Commissioning or Re-tuning™ measures (AIRCx)
  - Intelligent Load Control (ILC)
  - Transactive Control and Coordination (TCC)
  - Renewable integration

EE

GS

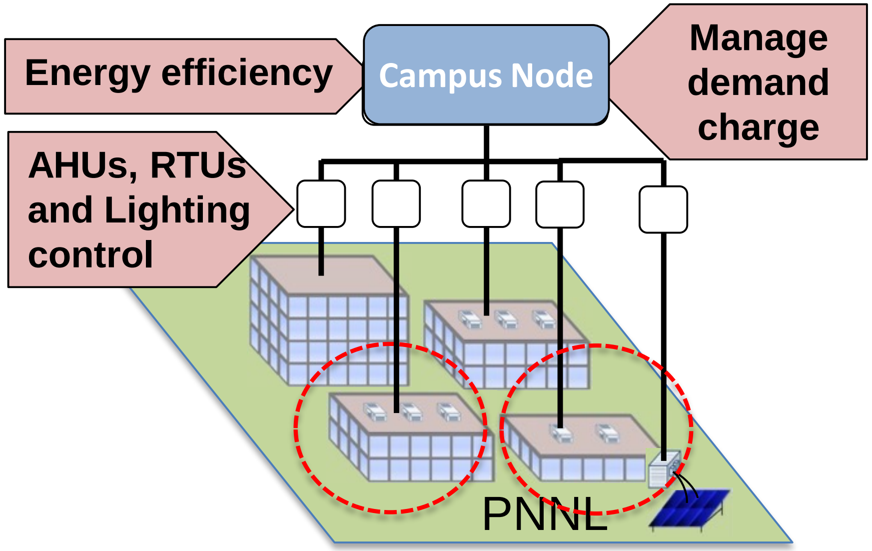


- Developed simulation environment for testing grid services
- Deployed VOLTTRON on PNNL campus buildings
  - Started deploying energy efficiency and grid services
- Tested grid services in a simulation environment
- Worked with PNNL Facilities and Operations and developed risk-mitigation strategies

Progress 2017: Testing EE services and GSs in Individual Buildings

Focus is on Behind-the-Meter Technologies and Individual Buildings

- Extended EE services and GSs
  - 12 buildings; combination of large and small; systems include variable air volume (VAV) air-handling units (AHUs), packaged rooftop units (RTUs) and lighting; buildings with building automation system (BAS) and without
- Developed a methodology to aggregate AFDD results
- Enhanced ILC to support additional use cases
- Developed VOLTTRON market service within a building
- Prepared 4 technical documents for technologies developed; published 6 peer reviewed journal papers
- Added two more universities (CWRU and U-Toledo)
  - 8 buildings, 130 kWh/120 kW BESS and 1 MW PV
  - 2 buildings and 65 kWh/120 kW BESS



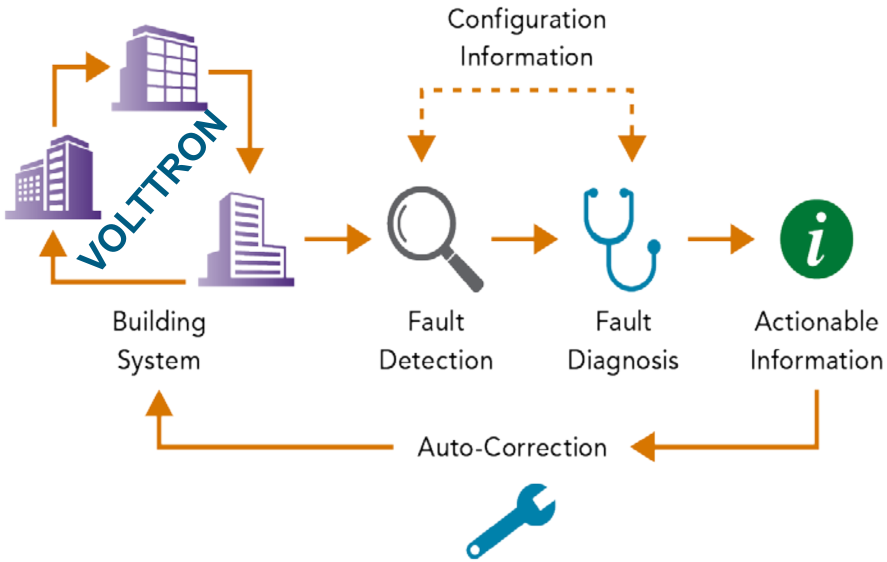
Energy efficiency

Campus Node

Manage demand charge

AHUs, RTUs and Lighting control

Progress: AFDD, AIRCx and Auto-Correction EE Services

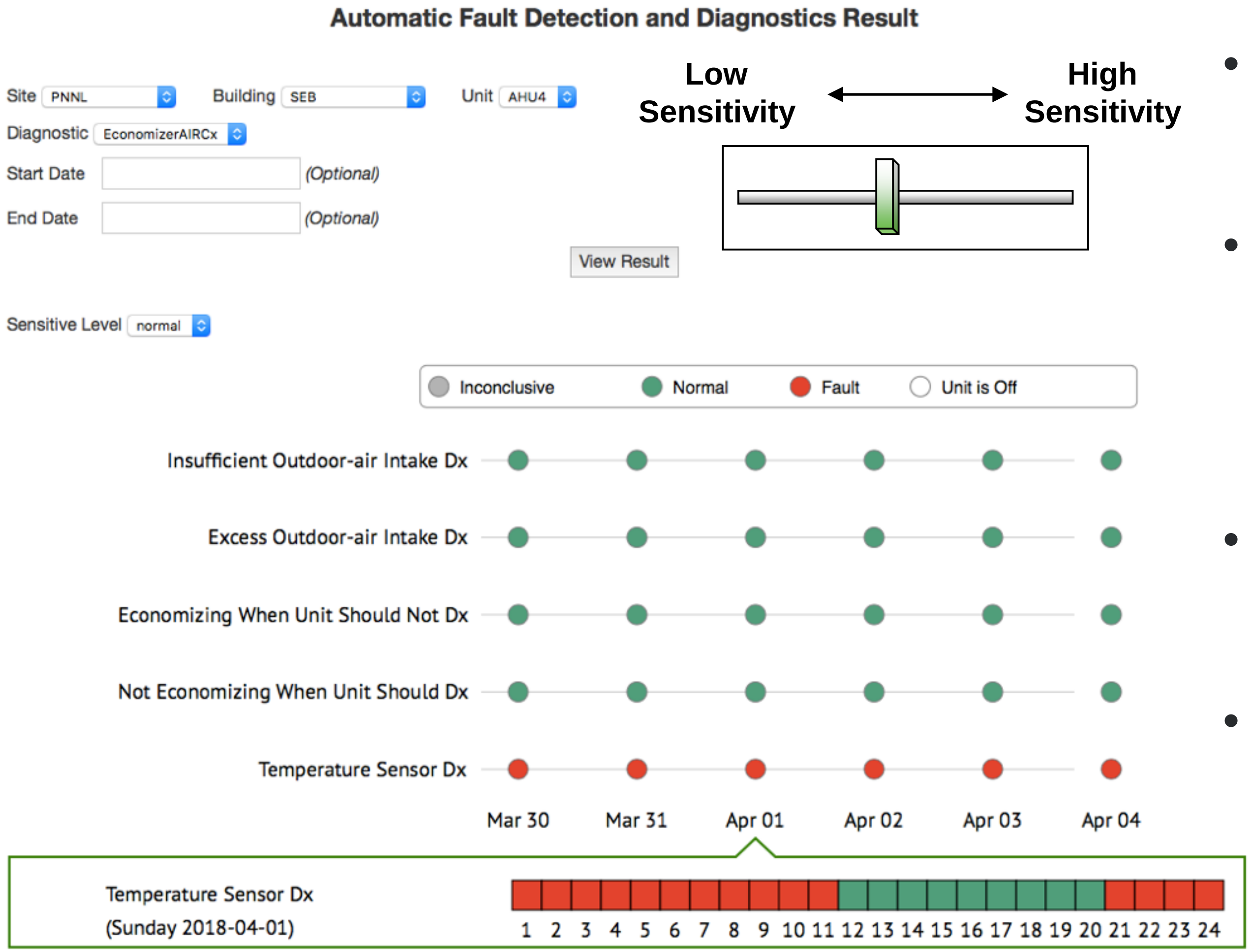


Katipamula S, RG Lutes, G Hernandez, JN Haack, and BA Akyol. 2016. "**Transactional Network: Improving Efficiency and Enabling Grid Services for Building.**" Science and Technology for the Built Environment (2016), 22(6), pp 643-654 doi:10.1080/23744731.2016.1171628

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 (2016) 00, 1–11 doi: 10.1080/23744731.2016.1218236

- Engineering principles of air-handling unit (AHU) operations are used to detect and diagnose faults
- AFDD applications work on both AHUs and RTUs, while the AIRCx applications are for multi-zone VAV systems
- Because systems lack physical redundancy, analytical redundancy is created, where possible
- Testing conducted in 10 PNNL buildings (>20 AHUs and 10 RTUs); results indicate algorithms have been highly successful in consistently identifying faults in building operations

Progress: AFDD and AIRCx Results



Automatic Fault Detection and Diagnostics Result

Site PNNL Building SEB Unit AHU4

Diagnostic EconomizerAIRCx

Start Date (Optional)

End Date (Optional)

Sensitive Level normal

	Mar 30	Mar 31	Apr 01	Apr 02	Apr 03	Apr 04
Insufficient Outdoor-air Intake Dx	🟢	🟢	🟢	🟢	🟢	🟢
Excess Outdoor-air Intake Dx	🟢	🟢	🟢	🟢	🟢	🟢
Economizing When Unit Should Not Dx	🟢	🟢	🟢	🟢	🟢	🟢
Not Economizing When Unit Should Dx	🟢	🟢	🟢	🟢	🟢	🟢
Temperature Sensor Dx	🔴	🔴	🔴	🔴	🔴	🔴

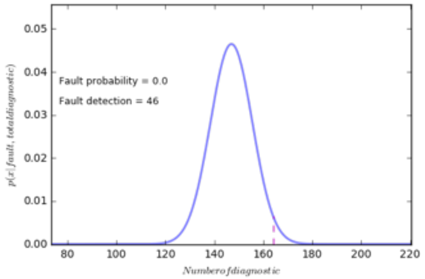
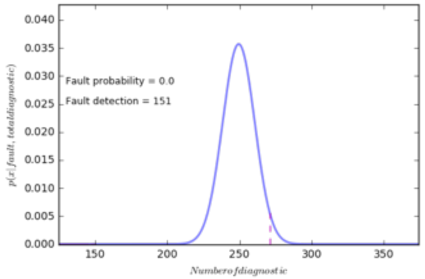
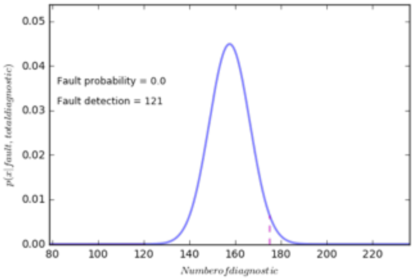
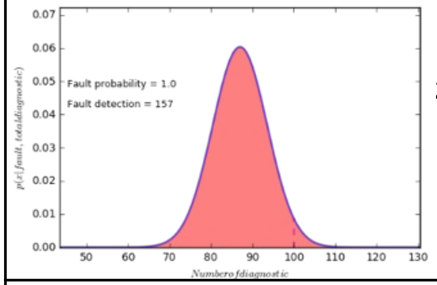
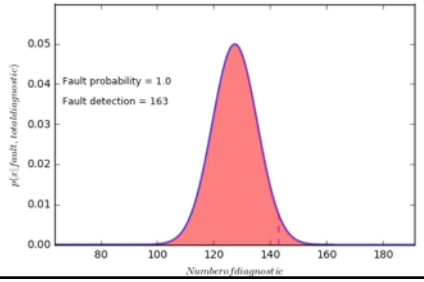
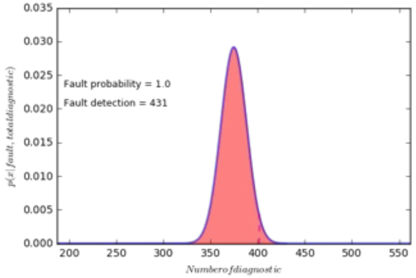
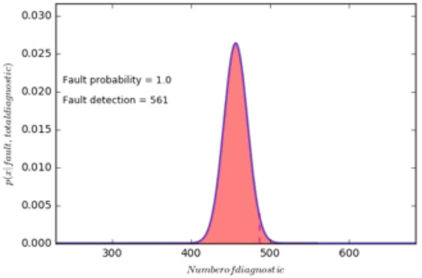
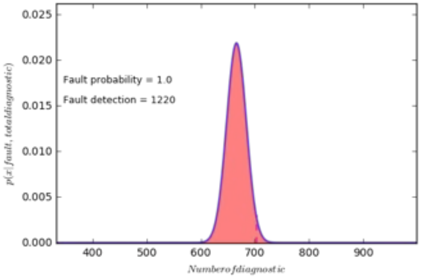
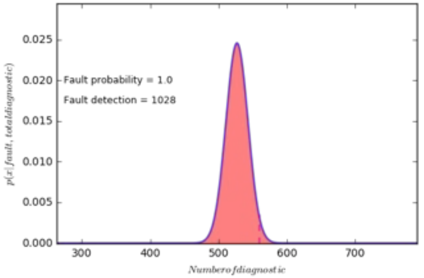
● Inconclusive 🟢 Normal 🔴 Fault ○ Unit is Off

Temperature Sensor Dx
(Sunday 2018-04-01)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟥	🟥

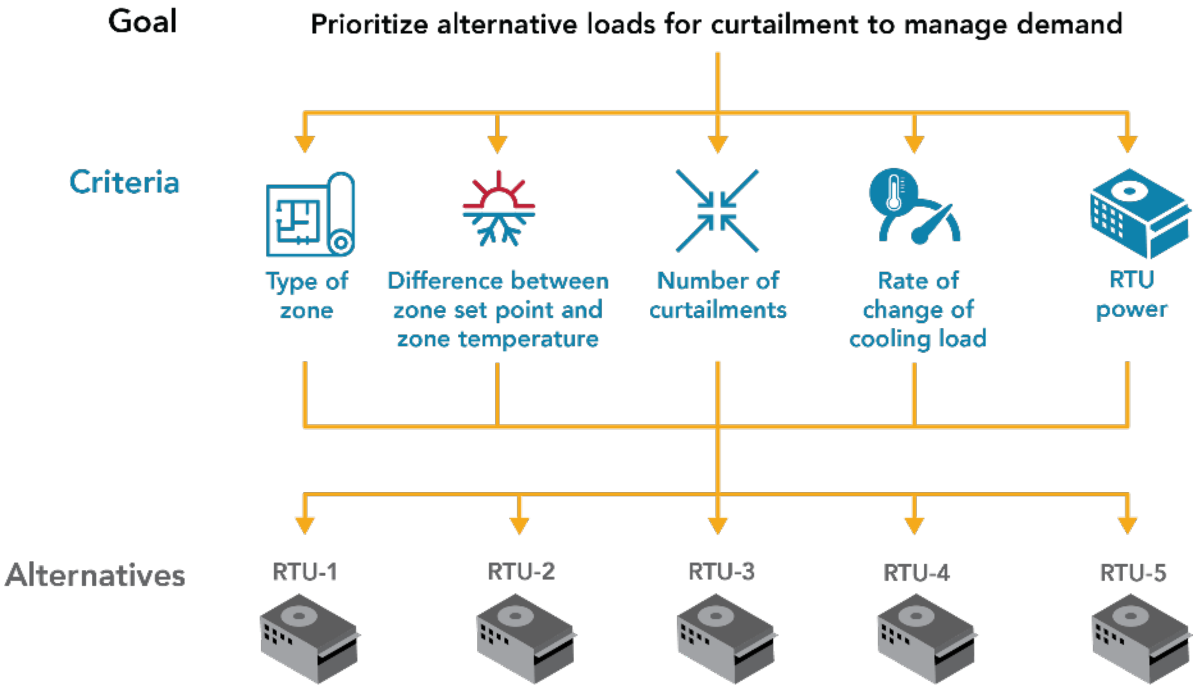
- Detection and diagnostic thresholds are hard to establish
- Even with user adjustable thresholds, single hour diagnostics error codes can be misleading
- Proactive diagnostics overcomes some of these issues
- AFDD error aggregation also provides a better solution

Progress: Not Economizing when Unit Should Low Sensitivity

April	May	June
 **Energy impact: 9.0 [kWh]**	 **Energy impact: 26.7 [kWh]**	 **Energy impact: 19.8 [kWh]**
July (Fault)	**August (Fault)**	**September (Fault)**
 **Energy impact: 29.4 [kWh]**	 **Energy impact: 26.0 [kWh]**	 **Energy impact: 98.8 [kWh]**
October (Fault)	**November (Fault)**	**December (Fault)**
 **Energy impact: 155.5 [kWh]**	 **Energy impact: 446.4 [kWh]**	 **Energy impact: 497.0 [kWh]**

Progress GS Technology: Intelligent Load Control

New automated agent-based control method for prioritizing controllable end-use loads for peak load management, dynamic load shaping or transactive control



Goal Prioritize alternative loads for curtailment to manage demand

Criteria

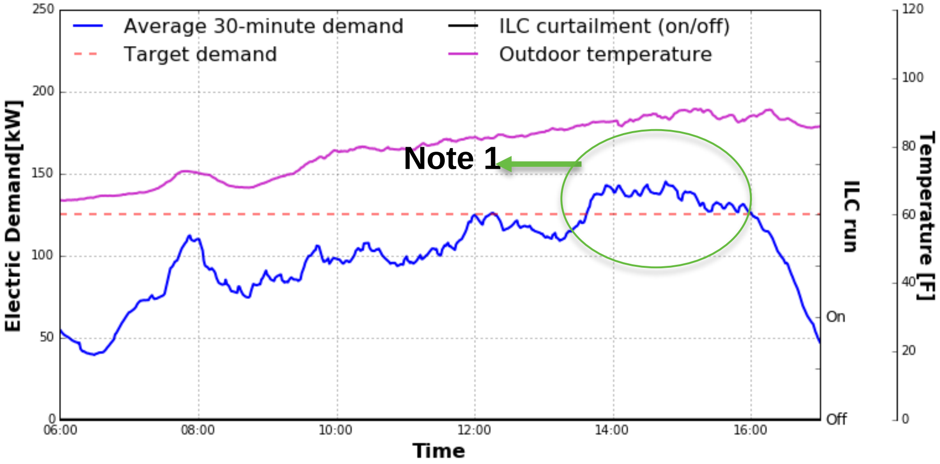
- Type of zone
- Difference between zone set point and zone temperature
- Number of curtailments
- Rate of change of cooling load
- RTU power

Alternatives RTU-1, RTU-2, RTU-3, RTU-4, RTU-5

Kim W, and S Katipamula. 2017. "**Development and Validation of an Intelligent Load Control Algorithm.**" Energy and Buildings, 135 (2016), pp 62-73. http://dx.doi.org/10.1016/j.enbuild.2016.11.040

Progress: ILC Test During Cooling Season

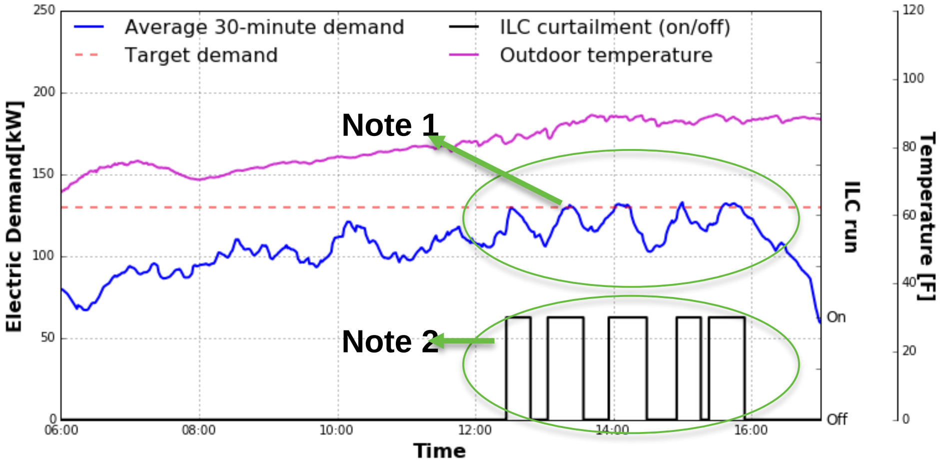
Business-As-Usual, No ILC: July 12



- **Note 1**: Peak demand for this day is 145 kW, which occurred between 2 p.m. and 4 p.m.
- Also, note that the duration of the peak demand was significant in this case

- **ILC also supports capacity bidding and transactive control use cases**

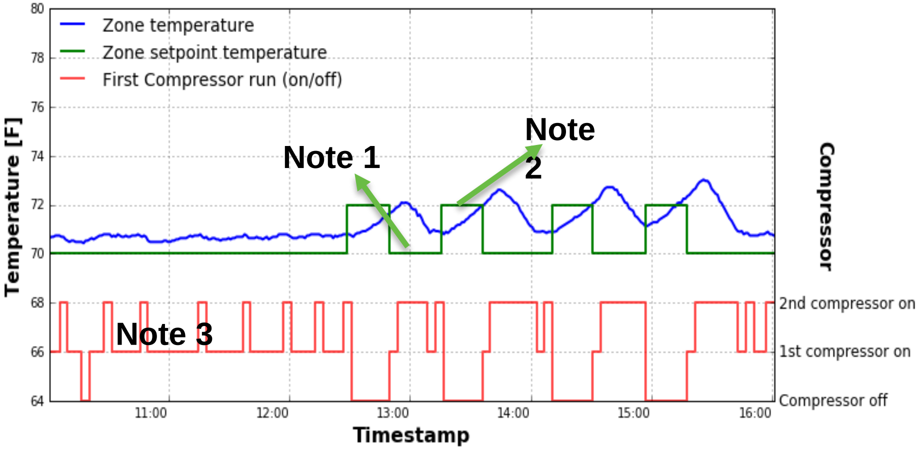
Dynamic Load Shaping with ILC: July 11



- **Note 1:** Peak demand for this day **never exceeds** the target of 135 kW, which was set several times between 12:30 p.m. and 4 p.m.
- **Note 2**: Some end-use loads were turned off to manage the load shape
- If ILC were operational the previous day, the building could have avoided approximately $50 in Pacific Northwest or $200 in CA or NY

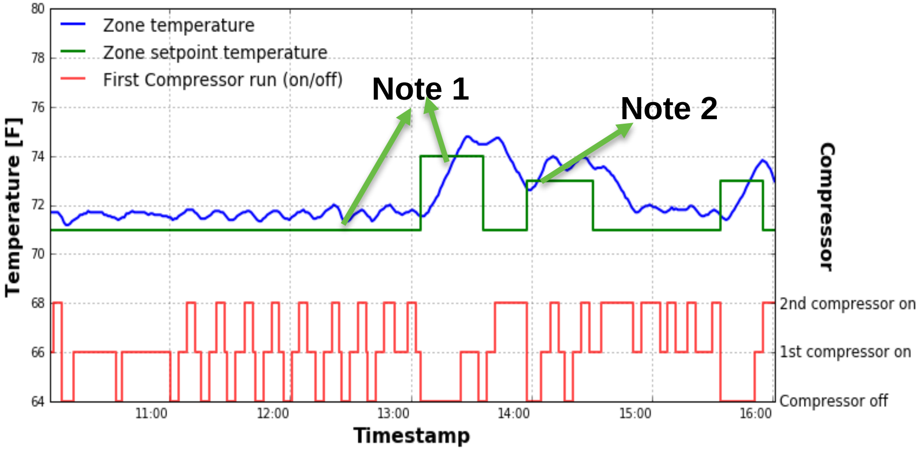
Progress: ILC Temperature Profile and Heat Pump Status - Cooling Season

Heat Pump 4



- **Note 1**: Normal cooling set point is 70° F for this heat pump
- **Note 2**: When ILC wants to control the unit, it increases the set point to 72° F
- **Note 3**: Heat pump status
- Note the set point excursions are modest. To get the desired result, extending set point excursions to 2° F or 3° F will result in deeper load management

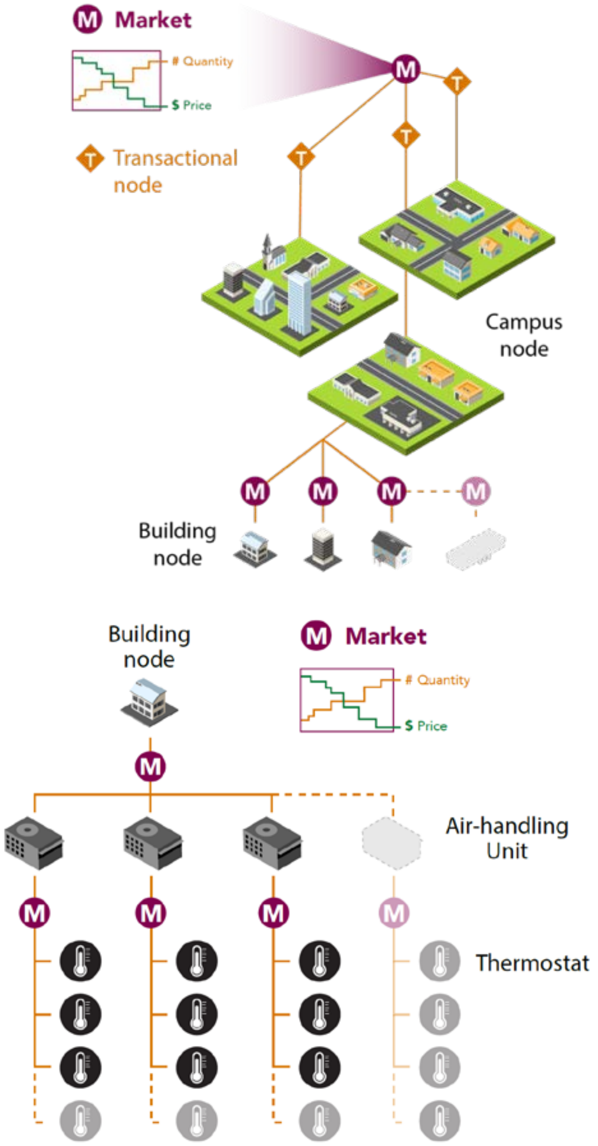
Heat Pump 8



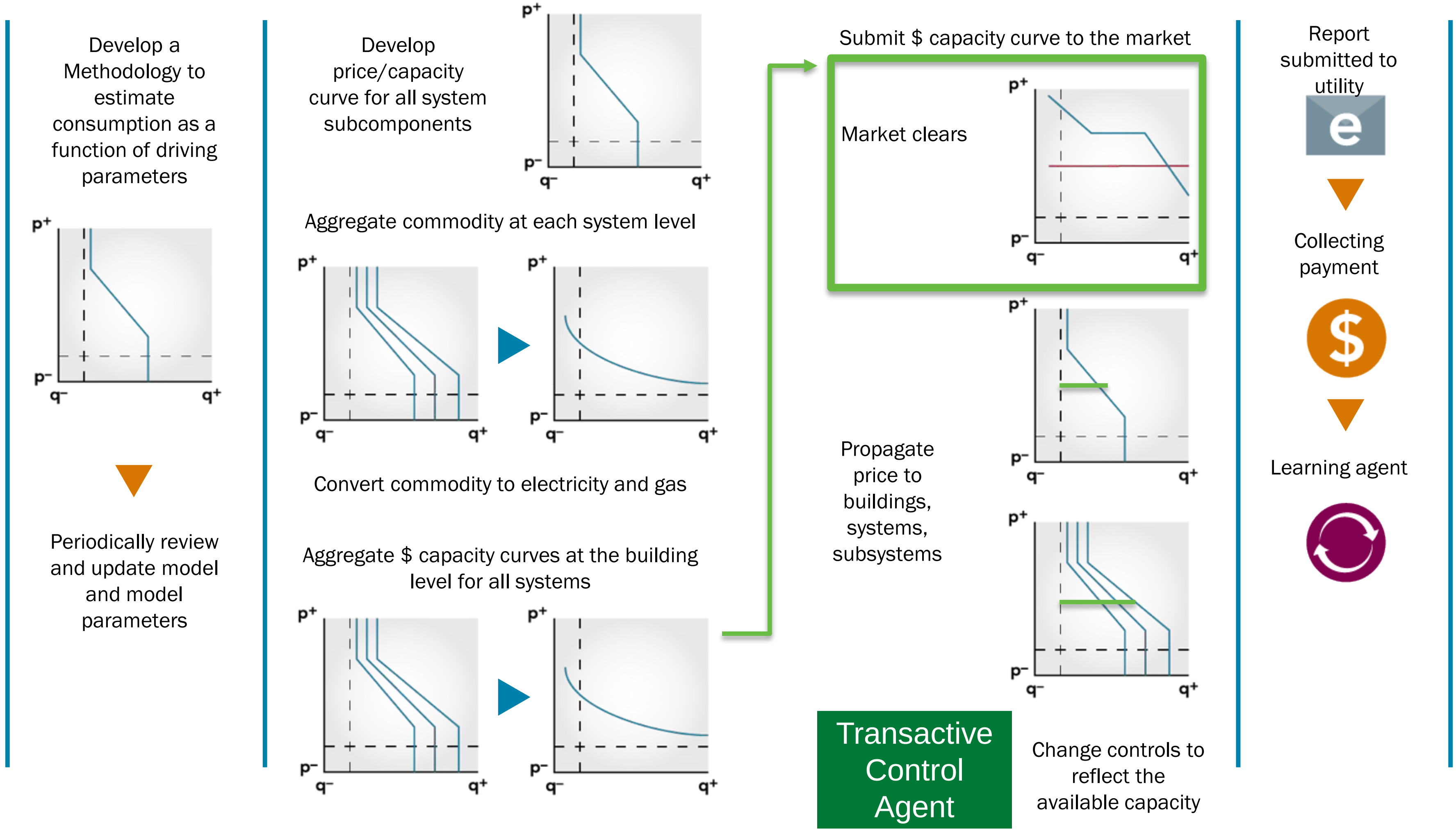
- **Note 1**: Normal cooling set point 71° F and the set point was increased to 73/74° F (stage 1/2) for load management
- **Note 2**: Although the unit was supposed to be OFF, it is released as soon as the zone temperature exceeds the set point

GS Service Technology: Transactive Control and Coordination (TCC)

- Use of “signals” from external markets to create markets at campus and individual building level, result in better management of energy consumption, lower energy cost, potentially improve comfort and result in a more reliable electric grid
- Controllable devices, such as, RTUs, AHUs, hot water heaters, variable-air-volume boxes serving building zones and devices become markets that “negotiate” prices and service level
- Tested on buildings with AHU, RTUs, dimmable lighting; results confirm the ability of this method to achieve experimental objectives



TCC Work Flow Inside a Building



Pre-TCC

Develop a Methodology to estimate consumption as a function of driving parameters

Periodically review and update model and model parameters

During TCC

Develop price/capacity curve for all system subcomponents

Aggregate commodity at each system level

Convert commodity to electricity and gas

Aggregate $ capacity curves at the building level for all systems

Submit $ capacity curve to the market

Market clears

Propagate price to buildings, systems, subsystems

Change controls to reflect the available capacity

Transactive Control Agent

Post-TCC

Report submitted to utility

Collecting payment

Learning agent

Stakeholder Engagement

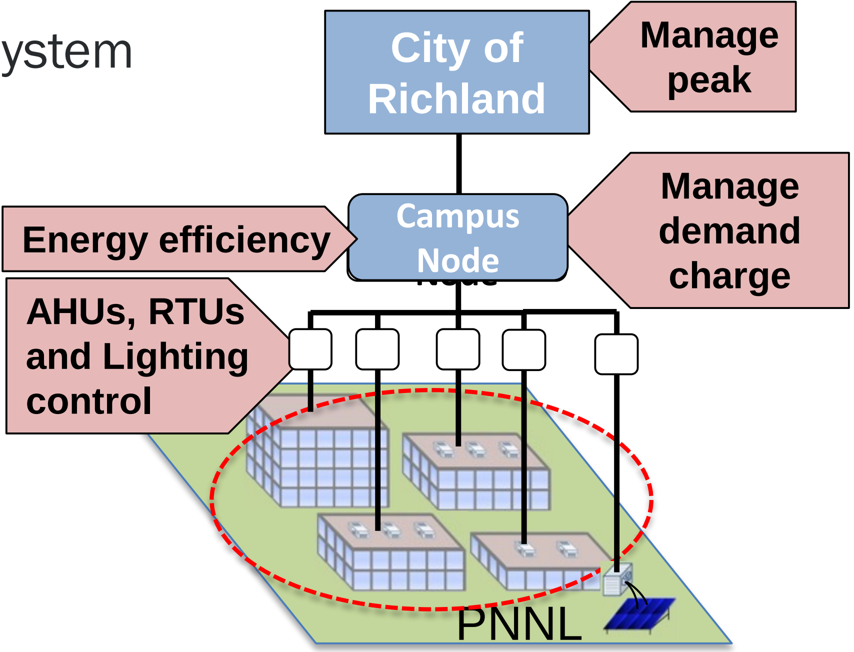
Early stakeholder involvement is key to successful technology adoption

- The planned 5-year project is about halfway complete
- The project team has quarterly meetings with utility representatives and energy service providers
- An advisory committee made up of representatives of Seattle City Light, Puget Sound Energy, Avista Corp, City of Richland, McKinstry and Transformative Wave Technologies; other stakeholders will be added before field-validation begins
  - Review progress and ensure technologies being developed are relevant to their current and future needs
- **Communications:** The project team has already published 4 technical reports, 2 user guides, 6 journal papers and identified a number of additional papers and publications that will be presented at conferences or published in research journals

Ongoing 2018: Testing of EE and GS in Multiple Buildings and Across the Meter

Focus is on Both Sides of the Meter and Multiple Buildings with Transactive Market System

- Integration of additional smart grid assets
  - Environmental test chambers, thermal energy storage system (TESS) and BESS; and control upgrades
- Developing single time step price-capacity curves for various end uses
- Extending grid services testing to multiple buildings coordinated with a transactive market system and City of Richland objectives
- Continuing VOLTTRON deployment and EE experiments
- Developing generic transactive market system
- Enhancing modeling approaches using machine learning techniques
- Developing simulation environment to study signal volatility
- Extending experiments at partners' sites



City of Richland

Manage peak

Campus Node

Energy efficiency

Manage demand charge

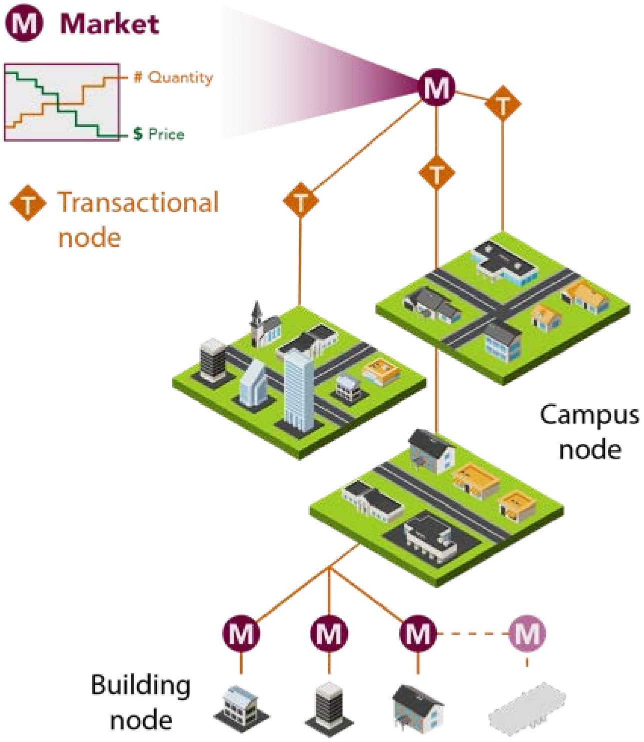
AHUs, RTUs and Lighting control

PNNL

Planned 2019: Validation of EE Services and GSs at Distribution Scale

Focus is on Both Sides of the Meter and Validation of “Recipes of Replication” and Scalability Using Transactive Market System

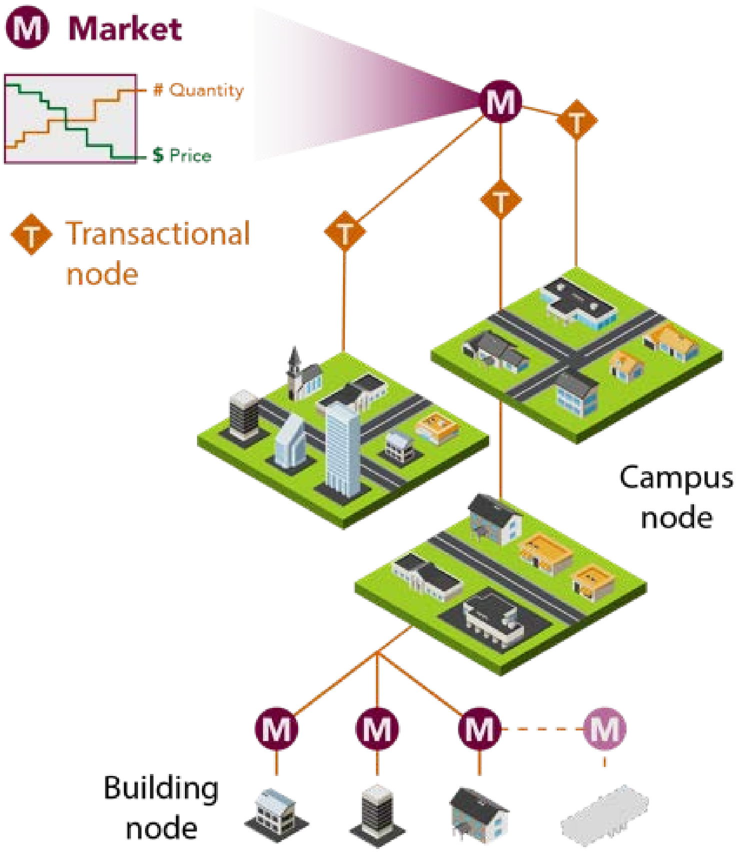
- Test GSs across multiple campuses using transactive market system
- Develop additional transactive market system use cases
- Develop generalized approaches for creating multi-time-step price-capacity curves for end uses
- Extend and document transactive controls for renewable integration
- Enhance fundamental building blocks for transactive controls – prices-capacity curves, load forecasting models, etc.
- Develop settlement concepts
- Develop a validation plan to test “recipes of replication” and identify utility/other partners that will support the effort



Planned 2019: Validation of EE Services and GSs at Distribution Scale

Focus is on Both Sides of the Meter and Validation of "Recipes of Replication" and Scalability Using Transactive Market System

- Complete enhancement of the fundamental building blocks for transactive controls – prices-capacity curves, load forecasting models, etc.
- Test settlement concepts
- Validate "recipes of replication" at distribution scale working with utility/other partners and Commercial Building Integration Program



Thank You

Pacific Northwest National Laboratory, Washington State University, University of Washington, Case Western Reserve University, and University of Toledo

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REFERENCE SLIDES

Project Budget

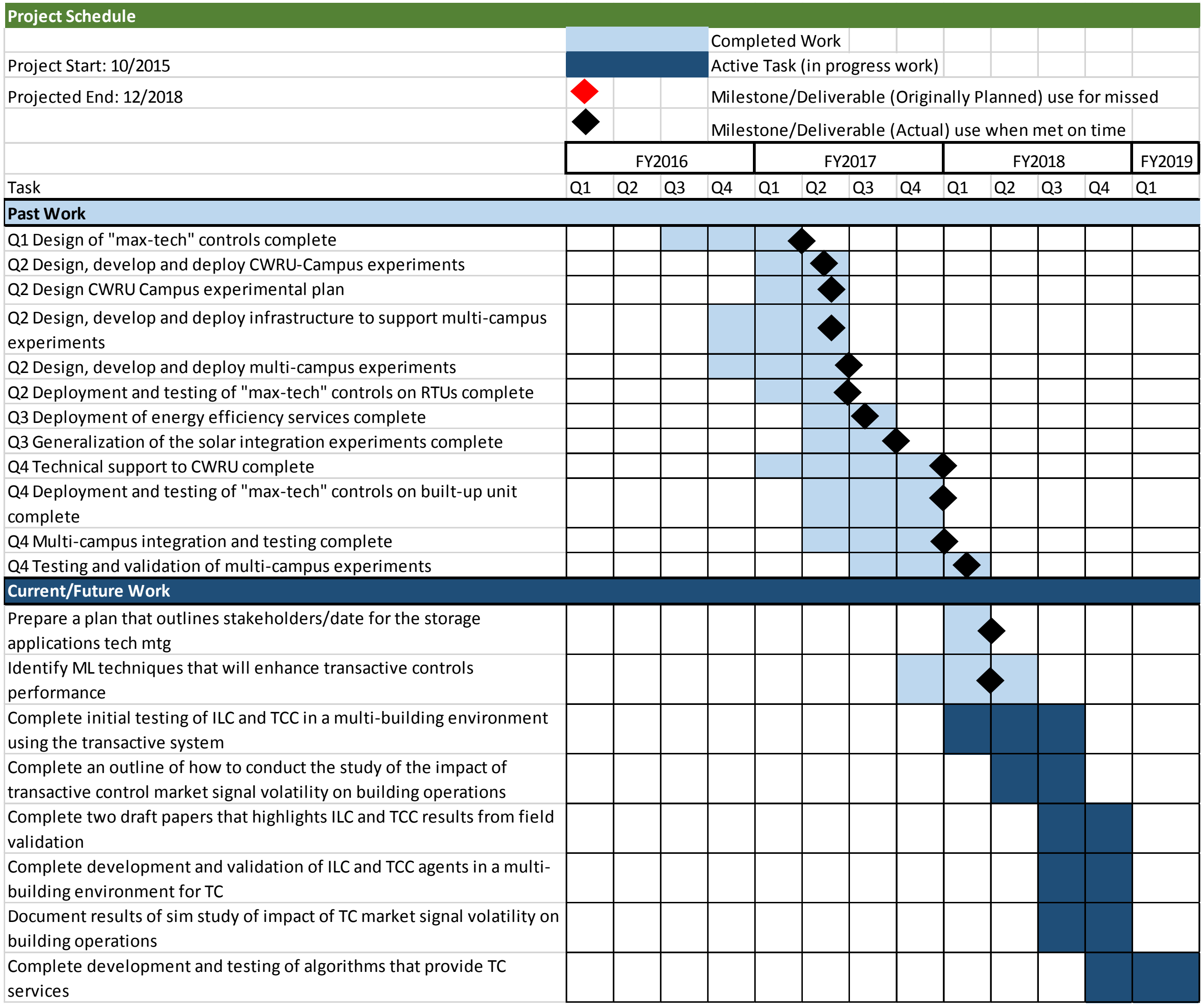
Project Budget: $5,700K
Variances: No variances
Cost to Date: Cost through March 2018, totals $3,540K
Additional Funding: Of total $5,700K project budget, new FY18 BA to be received by PNNL is $890K
FY16 – UW and WSU
FY17 – CWRU and U-Toledo
FY18 – WSU, CWRU and U-Toledo

Budget History					
FY 2016– FY 2017 (past)		FY 2018 (current)		FY 2019 – 12/31/2018 (planned)	
DOE	*Cost-share	DOE	*Cost-share	DOE	*Cost-share
$2,700K	$2,750K	$2,500K	$2,525K	$500K	$500K

*Washington State Department of Commerce and DOE Office of Electricity

Project Plan and Schedule

- **Project started in 10/2015 and is scheduled for completion of testing transactive control algorithms in 12/2018**
- **Schedule and Milestones (see table below)**
- **All milestones and deliverables are on track**



Project Schedule

Project Start: 10/2015

Projected End: 12/2018

░ Completed Work

█ Active Task (in progress work)

♦ Milestone/Deliverable (Originally Planned) use for missed

◆ Milestone/Deliverable (Actual) use when met on time

	FY2016				FY2017				FY2018				FY2019
Task	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1
Past Work													
Q1 Design of "max-tech" controls complete			░	░	░ ◆								
Q2 Design, develop and deploy CWRU-Campus experiments					░	░ ◆							
Q2 Design CWRU Campus experimental plan					░	░ ◆							
Q2 Design, develop and deploy infrastructure to support multi-campus experiments				░	░	░ ◆							
Q2 Design, develop and deploy multi-campus experiments				░	░	░ ◆							
Q2 Deployment and testing of "max-tech" controls on RTUs complete					░	░ ◆							
Q3 Deployment of energy efficiency services complete						░	░ ◆						
Q3 Generalization of the solar integration experiments complete						░	░ ◆						
Q4 Technical support to CWRU complete					░	░	░	░ ◆					
Q4 Deployment and testing of "max-tech" controls on built-up unit complete						░	░	░ ◆					
Q4 Multi-campus integration and testing complete						░	░	░ ◆					
Q4 Testing and validation of multi-campus experiments							░	░	░ ◆				
Current/Future Work													
Prepare a plan that outlines stakeholders/date for the storage applications tech mtg									░ ◆				
Identify ML techniques that will enhance transactive controls performance								░	░ ◆	░			
Complete initial testing of ILC and TCC in a multi-building environment using the transactive system									█	█	█		
Complete an outline of how to conduct the study of the impact of transactive control market signal volatility on building operations										█	█		
Complete two draft papers that highlights ILC and TCC results from field validation											█	█	
Complete development and validation of ILC and TCC agents in a multi-building environment for TC											█	█	
Document results of sim study of impact of TC market signal volatility on building operations											█	█	
Complete development and testing of algorithms that provide TC services												█	█

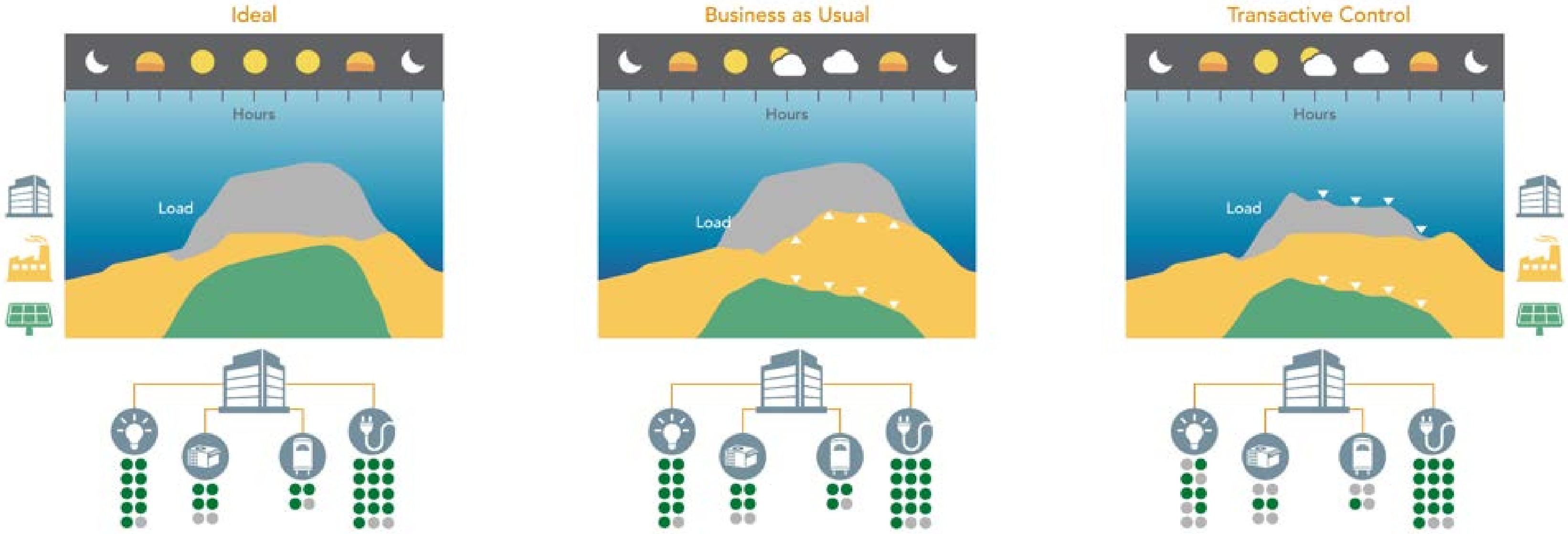
Backup Slides

Progress: List of AFDD and AIRCx Applications

- AFDD applications:
  - Air Temperature Sensor Fault
  - AHU/RTU is not Fully Economizing When it Should
  - AHU/RTU Economizing When it Should Not
  - Excess Outdoor Air Intake
  - Insufficient Outdoor Air Intake
- AIRCx applications:
  - Low Duct Static Pressure
  - High Duct Static Pressure
  - No Duct Static Pressure Set Point Reset
  - Static Pressure Control
  - Low Supply Air Temperature
  - High Supply Air Temperature
  - No Supply Air Temperature Reset
  - Supply Air Temperature Control
  - Schedule - Unoccupied Fan Operation or other systems
- Version of proactive diagnostics and auto-correcting AIRCx also available

Progress GS Technology: Integration of Distributed Renewable Generation

- Monitors solar production and its intermittency, including fluctuations that challenge grid operations, and concurrently engages variable-frequency-drives on fans, hot water heaters and other fast acting loads to adjust a building's power consumption to balance loads
- Laboratory testing successful in achieving experimental objectives



Control building loads such as variable-frequency-drives on fans in AHUs and packaged rooftop units to absorb renewables generation losses and reduce grid fluctuations

Building Efficiency Technology: AFDD and AIRCx

- **Experiment Status:** Designed, scripted in Python, tested through simulation and deployed on 12 buildings on the PNNL campus (since 2016)
- **Documentation:** Technical report completed and a draft of the user guide is also complete
- **Code:** Two main Python scripts represent this experiment:
  - a set of proactive diagnostics to detect economizer controls can be found in economizer_RCxAgent.py and
  - a set of proactive automated Re-tuning opportunities can be found in airside_retuning_rcx.py
- Example configuration files, required for both scripts, are also included in the repository. The v-agents also use a number of platform services, including *driver, scheduler, actuator, weather, etc*

Katipamula S, RG Lutes, RM Underhill, W Kim, S Huang. 2018. "**Automated Identification of Retro-Commissioning Measures.**" PNNL-27338, Richland, WA

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 (2016), 22(6), pp 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 (2016) 00, 1–11
doi: 10.1080/23744731.2016.1218236

Grid Service Technology: TCC

- **Experiment Status:** Designed, scripted in Python, tested through simulation and deployed on 4 buildings on the PNNL campus
- **Documentation:** Technical report completed and a draft of the user guide is also complete
- **Code:** A number of Python scripts represent this experiment; all of the code is also posted on the project Github site
- Example configuration files, required for all scripts, are also included in the repository. The v-agents also use a number of platform services, including *driver, scheduler, actuator, weather, etc.*

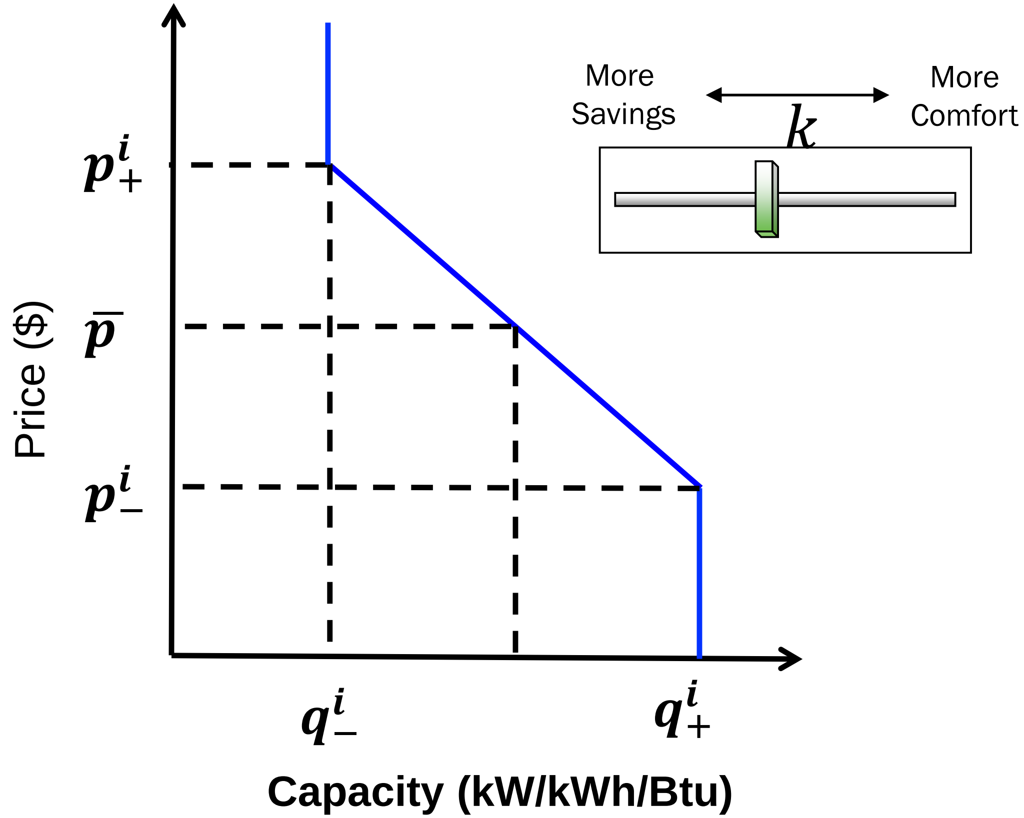
Corbin CD, A Makhmalbaf, G Liu, S Huang, VV Mendon, Zhao M, Somasundaram S, Ngo H, Katipamula S. 2016. "Transactive Control of Commercial Building HVAC Systems." PNNL-26083, Richland, WA.

Hao H, CD Charles, K Karanjit, and RG Pratt. 2017. "Transactive Control of Commercial Buildings for Demand Response," IEEE Transactions on Power Systems, 32(1), 774–783, January 2017

TCC: Generic Price-Capacity Curve

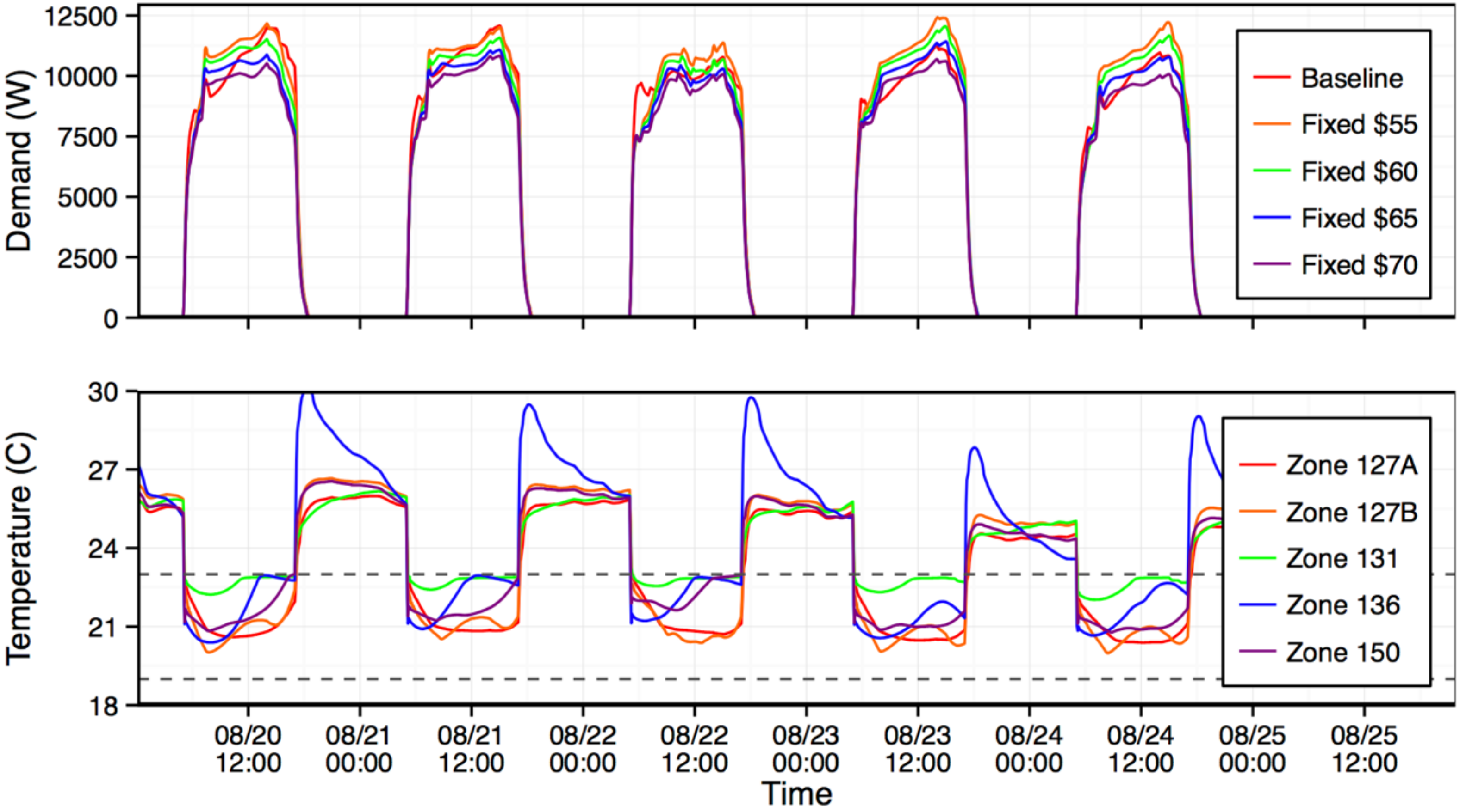
$$p_{+}^{i} = \bar{p} + k\sigma \longrightarrow$$

$$p_{+}^{i} = \bar{p} - k\sigma \longrightarrow$$



$\bar{p}$	Average price over a certain period
σ	Standard deviation of the price over the same period
k	User-specified tradeoff parameter (0 saving, >1 comfort)

TCC: Large Office Fixed Price Response



Higher the price, smaller the peak demand and energy use

GS Technology: ILC

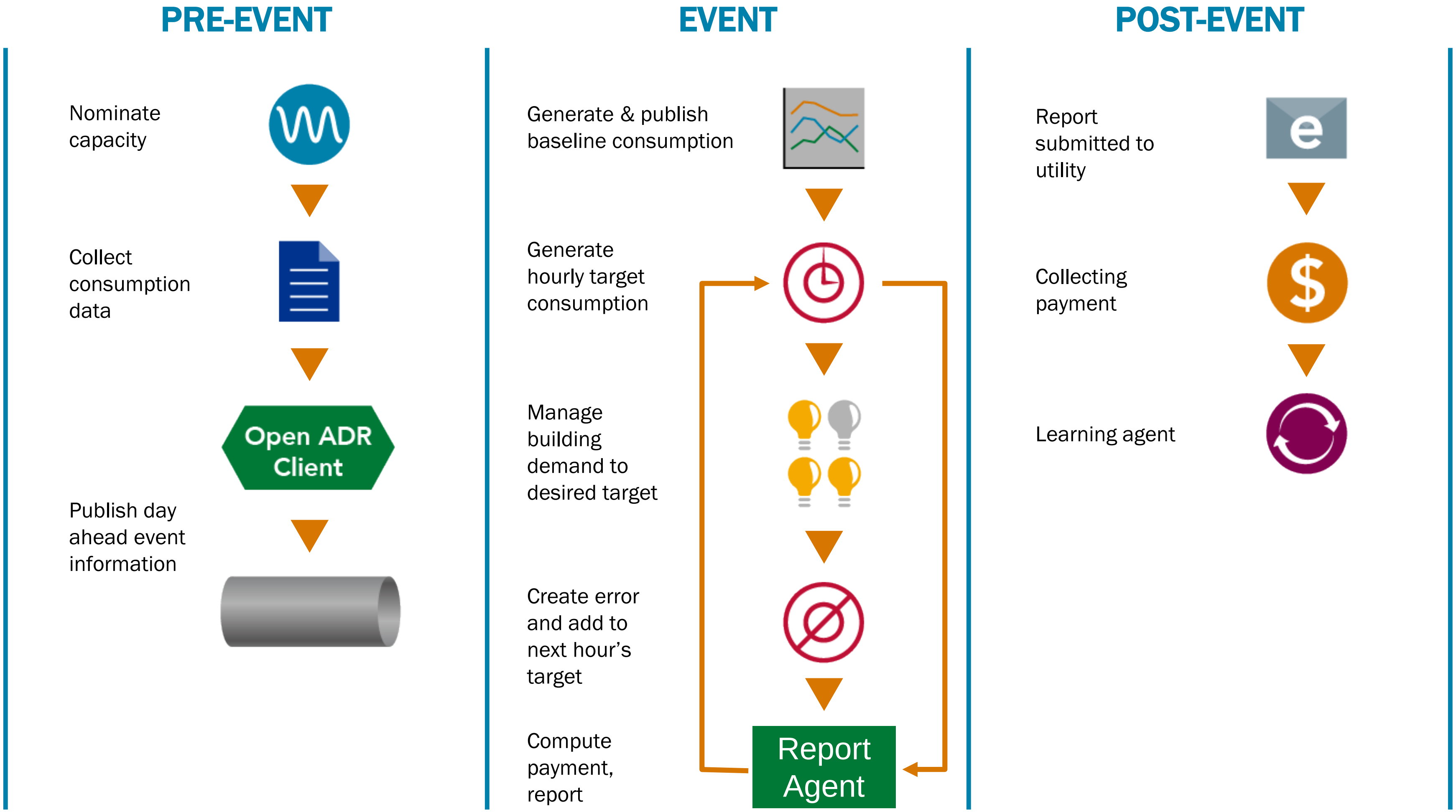
Intelligent Load Control (ILC)

- **Experiment Status:** Designed, scripted in Python, validated through simulation, and tested on three buildings on the PNNL campus
- **Documentation:** Technical report completed along with the user guide
- **Code:** Two main Python scripts required to run ILC
  - Peak electricity forecasting script (wbe.py)
  - The main ILC script (agent.py) for prioritizing and controlling loads
- Example configuration files are also included in the repository. These v-agents use a number of platform services, including *driver*, *scheduler*, *actuator*, etc.

Kim W, S Katipamula, RG Lutes, RM Underhill. 2016. "Behind the Meter Grid Services: Intelligent Load Control" PNNL-26034, Richland, WA.

Kim W, and S Katipamula. 2017. "**Development and Validation of an Intelligent Load Control Algorithm." Energy and Buildings**, 135 (2016), pp 62-73. http://dx.doi.org/10.1016/j.enbuild.2016.11.040

ILC: Capacity Bidding Sequence



PRE-EVENT

Nominate capacity

Collect consumption data

Open ADR Client

Publish day ahead event information

EVENT

Generate & publish baseline consumption

Generate hourly target consumption

Manage building demand to desired target

Create error and add to next hour's target

Compute payment, report

Report Agent

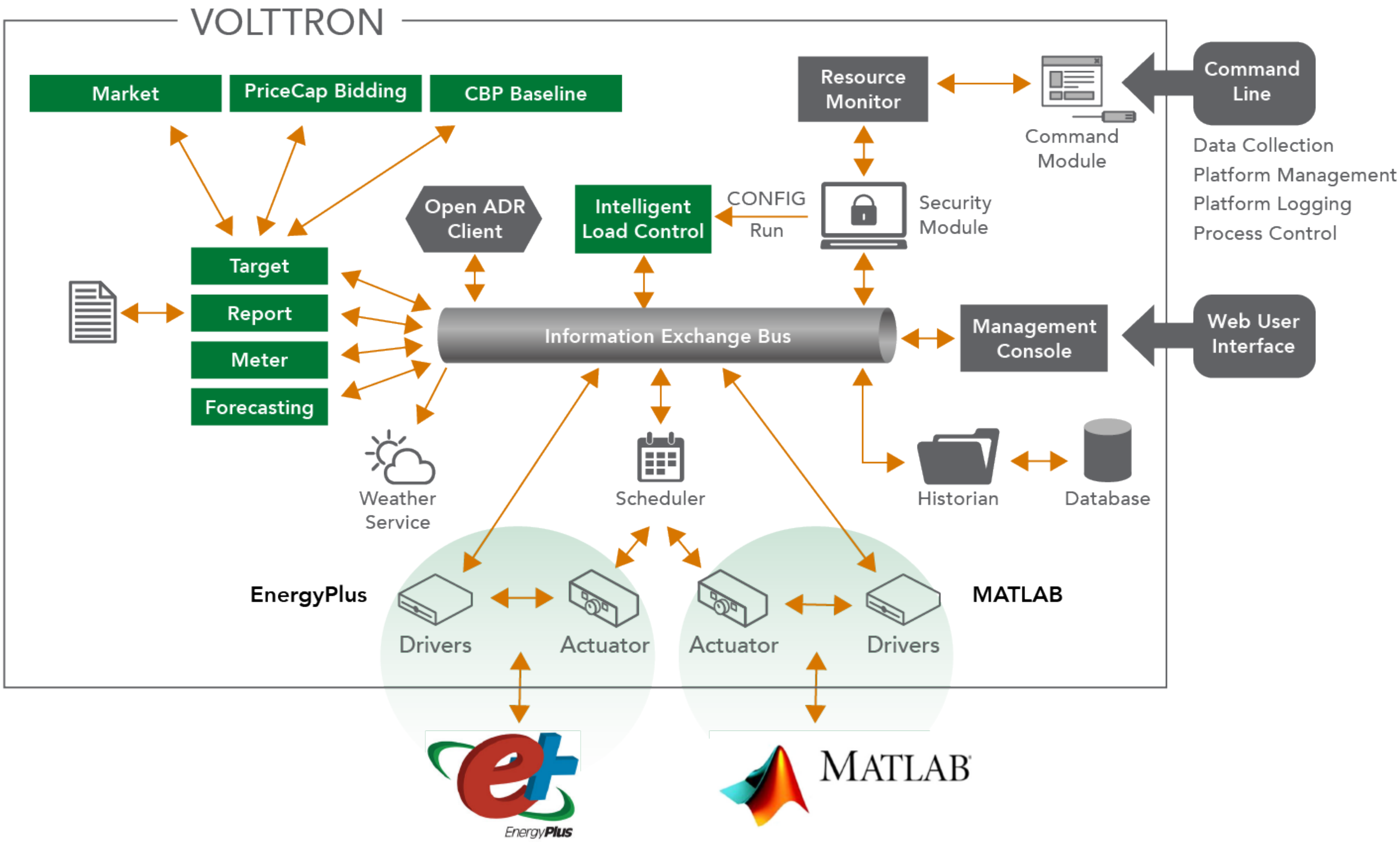
POST-EVENT

Report submitted to utility

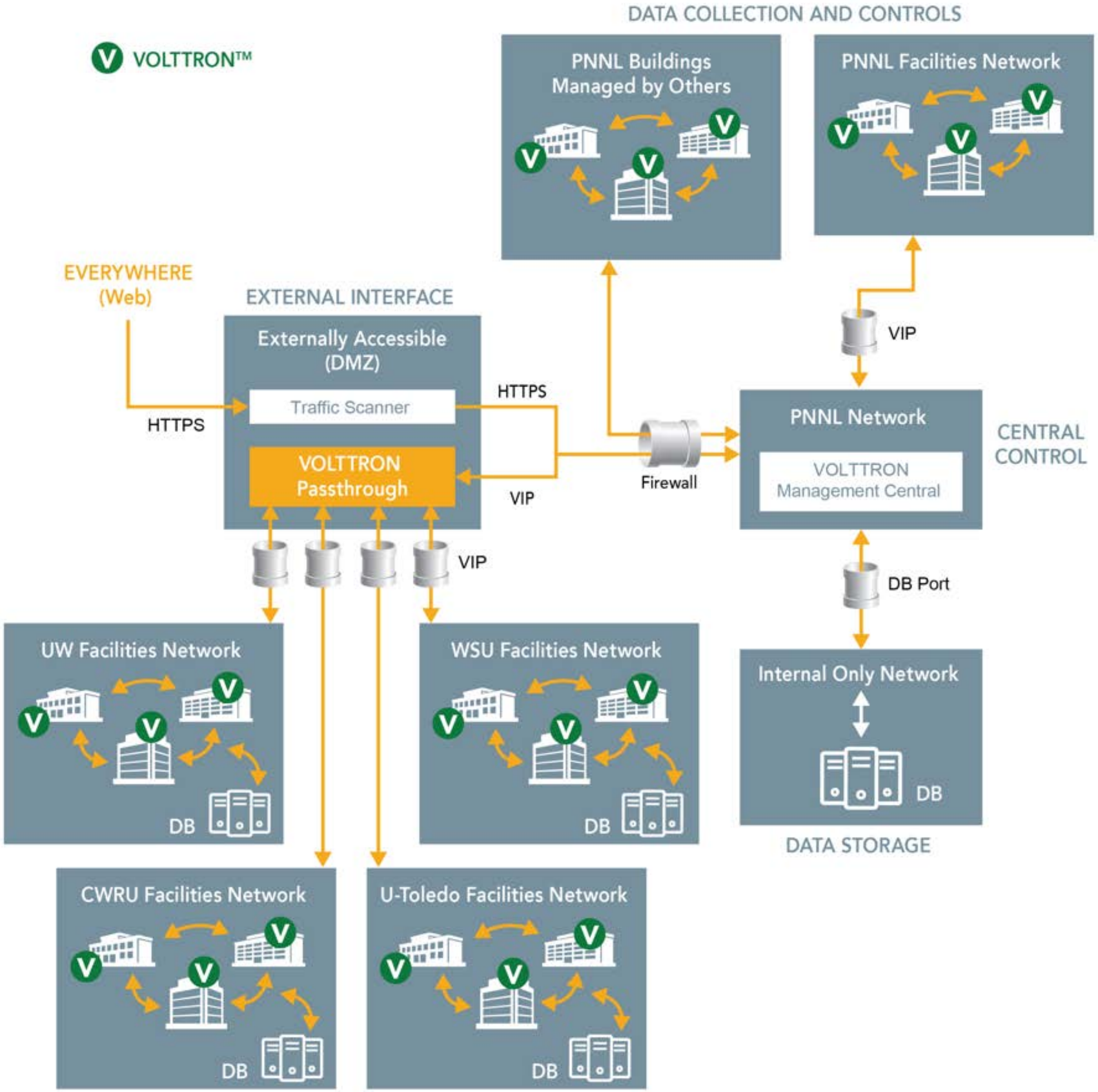
Collecting payment

Learning agent

ILC: Testing Agents in Simulation Environment



Approach: Network Infrastructure



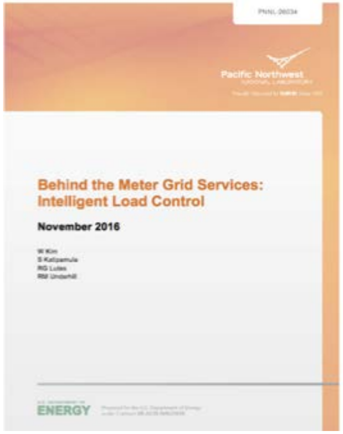
Publication to Date: Technical Reports, User Guides, Brochures/Fliers

Technical Reports and User Guides

- Kim W, S Katipamula, RG Lutes, RM Underhill. 2016. "Behind the Meter Grid Services: Intelligent Load Control" PNNL-26034, Richland, WA.
- Hao H, G Liu, S Huang, S Katipamula. 2016. "Coordination and Control of Flexible Building Loads for Renewable Integration; Demonstrations using VOLTTRON" PNNL-26082, Richland, WA.
- Corbin CD, A Makhmalbaf, G Liu, S Huang, VV Mendon, Zhao M, Somasundaram S, Ngo H, Katipamula S. 2016. "Transactive Control of Commercial Building HVAC Systems." PNNL-26083, Richland, WA.
- Katipamula S, RG Lutes, RM Underhill, W Kim, S Huang. 2018. "Automated Identification of Retro-Commissioning Measures."

Brochures/Fliers:

- "Clean Energy and Transactive Campus Project" (4-page brochure developed by PNNL, December 2016)
- A Blueprint for the Nation's Transactive Energy (2-page flier developed by PNNL, March 2016)

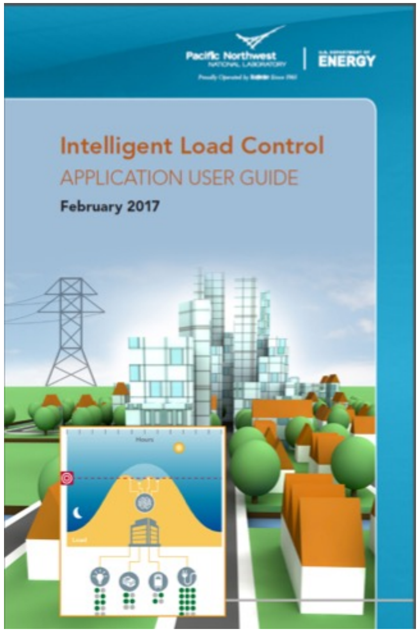

Pacific Northwest

Behind the Meter Grid Services:
Intelligent Load Control

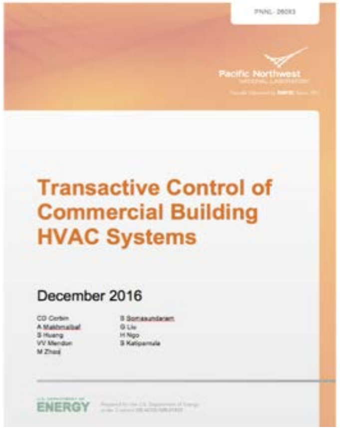
November 2016

W Kim
S Katipamula
RG Lutes
RM Underhill

ENERGY


Pacific Northwest | ENERGY

Intelligent Load Control
APPLICATION USER GUIDE
February 2017


Pacific Northwest

Transactive Control of
Commercial Building
HVAC Systems

December 2016

CD Corbin
A Makhmalbaf
S Huang
VV Mendon
M Zhao
S Somasundaram
G Liu
H Ngo
S Katipamula

ENERGY

Publications to Date: Journal and Magazine Articles

- Katipamula S, J Haack, G Hernandez, B Akyol and J Hagerman. 2016. "**VOLTTRON: An Open-Source Software Platform of the Future**," in IEEE Electrification Magazine, vol. 4, no. 4, pp. 15-22, Dec. 2016. doi: 10.1109/MELE.2016.2614178 URL:http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7725895&isnumber=7725795
- Kim W, and S Katipamula. 2017. "**Development and Validation of an Intelligent Load Control Algorithm.**" Energy and Buildings, 135 (2016), pp 62-73. http://dx.doi.org/10.1016/j.enbuild.2016.11.040
- Katipamula S, RG Lutes, G Hernandez, JN Haack, and B Akyol. 2016. "**Transactional Network: Improving Efficiency and Enabling Grid Services for Building.**" Science and Technology for the Built Environment (2016), 22(6), pp 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 (2016) 00, 1–11 doi: 10.1080/23744731.2016.1218236
- Hao H, CD Charles, K Karanjit, and RG Pratt. 2017. "**Transactive Control of Commercial Buildings for Demand Response**," IEEE Transactions on Power Systems, 32(1), 774–783, January 2017
- Charles DC, S Katipamula, D Varbie. 2017. "**Co-Simulation and Validation of Advanced Building Controls with VOLTTRON™ and EnergyPlus™**. Building Simulation 2017, San Francisco, CA.

Transactive Concepts Definitions (1)

These terms have been established in Building Technologies Office's public meetings and reference documents (through review and comment):

- **Transaction** – an exchange or interaction between entities, it can be:
  - Physical (in our case, energy + information)
  - Logical (in our case, controls or control systems that act on information)
  - Financial (in our case, a price to determine value to users)

- **Transactive Energy** – Gridwise Architecture Council definition - "techniques for managing the generation, consumption or flow of electric power within an electric power system through the use of economic or market-based constructs while considering grid reliability constraints"
  - The term "transactive" comes from considering that decisions are made based on a value to the parties involved. The decisions may be analogous to (or literally) economic transactions

Transactive Concepts Definitions (2)

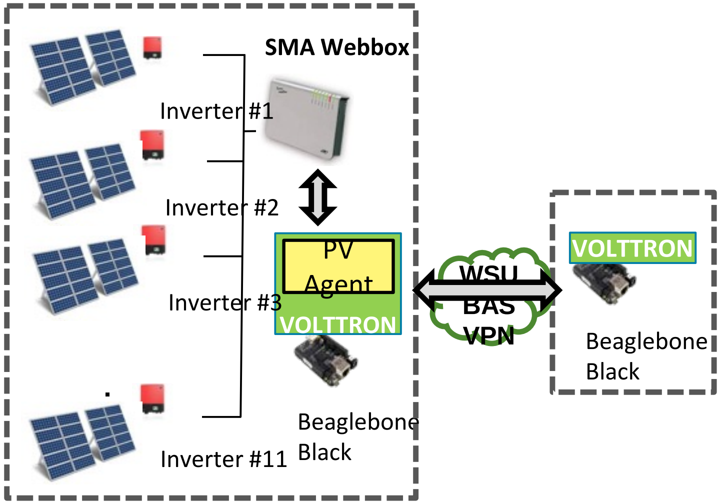
- **Transactive Devices** or **Connected Equipment** – consumer products with information and communication technologies (ICT) that enable them to be exercised through transactions – without boundaries
  - Many available technologies are typically proprietary (e.g., vendor specific ICT)

- **Transaction-Based Controls** – controls that exchange, negotiate, and respond to information through ICT
  - Most common signal is economics based: "price" (others include, renewable imbalance, frequency, voltage, etc.)
  - Needs advancements in fundamental sensors and controls – like plug-n-play, auto-mapping, etc.

- **Transactional Platform** – a software platform (e.g., ICT and related physical hardware) that allow applications to be programmed and negotiate/act on the exchange of information
  - An example platform, VOLTTRON™ is fully supported throughout DOE (OE, EERE, others) and is open source

WSU Phase I Overview

- **Installed at the WSU Research Foundation Building #2**
  - 243 PV modules
  - 345W per module = 83.8kW(dc)
- **Roof-mounted system (40%)**
  - Lowest installed cost; most kW for the $
- **Ground-mounted system (60%)**
  - Allows project visibility and access
  - Ability to do demonstrations and small experiments with shading and tilt
  - Visible equipment can be used for instruction on PV system design
- **VOLTTRON/PV integration**
  - Modbus communication between inverters and testbeds
- **Development of transactive energy auction**
  - Utilize real-time from inverter



WSU Phase II work

- **Task 1: Develop transactive energy use-cases**
  - Internal use cases
  - External use cases
- **Task 2: Design Internal Transactive Campus System**
  - Design transactive control architecture
    - Energy resources, algorithms, and communications
- **Task 3: Simulation of Transactive Campus Environment**
  - Internal case studies to compare
    - large vs. small buildings
    - stochastic laboratory buildings vs. fixed schedule buildings
    - Post energy retrofit buildings vs. pre- retrofit buildings
  - External case studies to compare:
    - End user benefits vs. utility benefits
    - Large microgrid user vs. single building

Northern Ohio Building-to-Grid Integration Demonstration: CWRU and U-Toledo

SCOPE

- Building-to-grid and transactive energy focus at DOE
- Multi-year project with initial funding of $900k from DOE, $400k from industry
- Three-site grid integration demonstration: CWRU, NASA, U of Toledo

OBJECTIVES

- Real-time optimization of building operation and energy transactions among building loads, battery energy storage systems, solar photovoltaic and wind
- Create value for utility through providing grid service, such as capacity/voltage/frequency management
- Develop a roadmap to replicate and scale at other sites

Year-1 Accomplishments – CWRU site

- **Integration of VOLTTRON with building automation system (BAS) in two buildings; testing advanced buildings algorithms (ILC and AIRCx)**
  - Currently conducting close-loop tests for both Olin and MSASS
  - Scraping nearly 4000 points at 5 – 15 minute periodicity and managing set point changes
- **EnergyPlus models developed for Olin and MSASS buildings EnergyPlus/ILC co-simulation for Olin**
- **JCI Battery installation and testing in Olin**
  - Installed 125kW/65kWh JCI battery in Olin building.
  - Interconnected battery to grid and successful demonstration of operation.
- **Established necessary IT connectivities within CWRU campus and with PNNL campus**
  - Firewall exceptions created for access to campus telemetry network from campus network. ICG can discover, monitor and control many buildings on campus. VOLTTRON can access energy meter data
  - Firewall exceptions created for in-bound and out-bound data traffic with PNNL
  - Installation of VOLTTRON Historian and CreateDB database on Amazon Web Service Cloud

Year-1 Accomplishments – NASA site

- **Developed an integrated distribution system simulation environment that includes GridLab-D, VOLTTRON and MATLAB**
  - Dynamic models of DER and other devices can be developed in MATLAB and then integrated with GridLab-D for dynamic system simulation at the second, or sub-second level

NASA Glenn Research Center
Cleveland, Ohio

Year-1 Accomplishments – U-Toledo site

- Completed device level HVAC inventory and map of power distribution/utility/IT interconnections at UT’s Scott Park Campus
  - Analyzed schematics, blueprints, schedules for building HVAC systems and BAS
  - Reconciled multiple generations of construction modifications, build-outs
  - Catalogued all existing plant equipment with relevant power ratings
  - Reconciled physical plant equipment with control system nomenclature from BAS side
- Converted proprietary BAS to BACnet compatibility (>8000 points)
- Modified campus’ IT network to support project and allow integration of grid-tied 1 MW PV array and Building Energy Storage System (BESS)
- Developed excellent working relationship with Constellation Energy (owner of PPA agreement for PV array) & Toledo Edison (grid connection of BESS)
- Deployed **10 interconnected VOLTTRON nodes** to collect data & control **9 buildings**