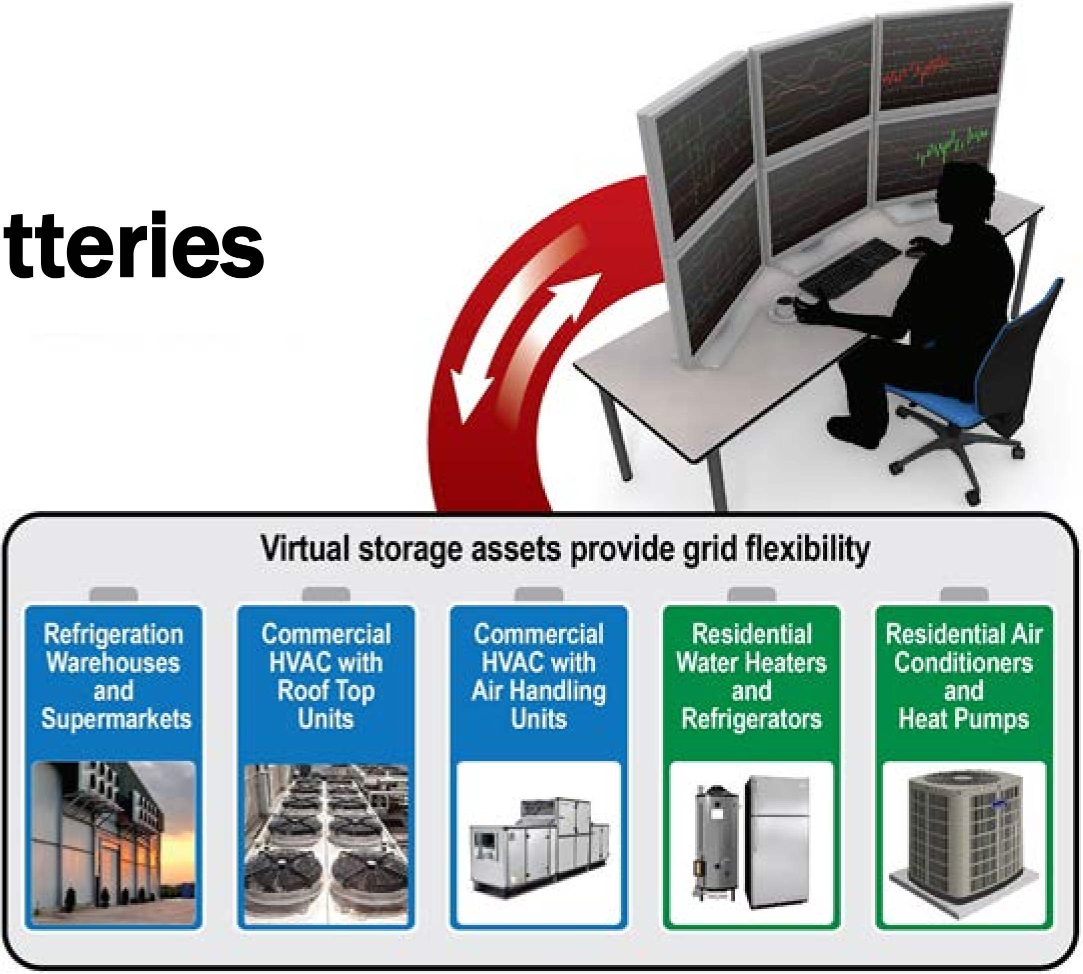
U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Virtual Batteries



Pacific Northwest National Laboratory
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Project Summary

Timeline:

Start date: April 2016

Planned end date: April 2019

Key Milestones

1. Flexibility characterization method for residential and commercial buildings (March 2017)
2. Virtual Battery Assessment Tool and regional VB potential from building loads in the U.S. (February 2018)
3. Field testing and validation; documentation of results (April 2019)

Budget:

Total Project $ to Date:

- DOE: $2.48M
- Cost Share: $0

Total Project $:

- DOE: $3M
- Cost Share: $0

Key Partners:

Oak Ridge National Laboratory (ORNL)
National Rural Electric Cooperative Association (NRECA)
University of Florida (UF)
Southern California Edison (SCE)

Project Outcome:

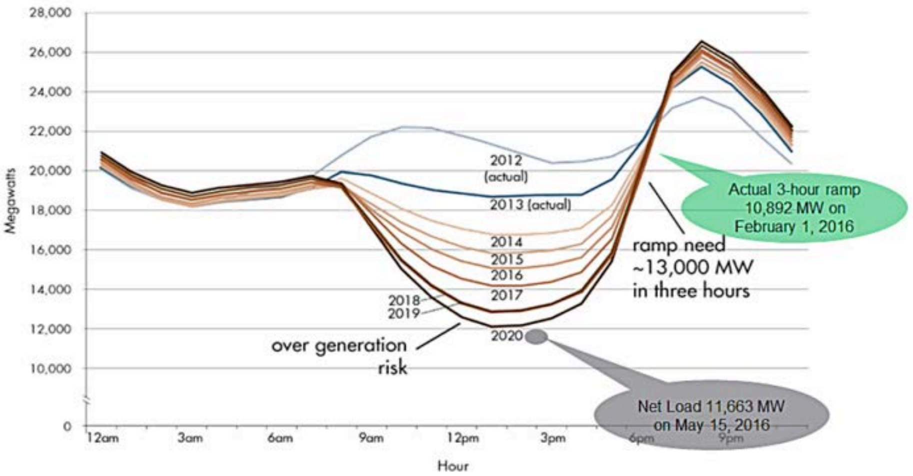
Enable utilities and building owners to use flexible building loads as virtual batteries (VBs) to provide grid and end-user services, integrate more renewable generation such as wind and photovoltaics into power systems, and improve building operational efficiency

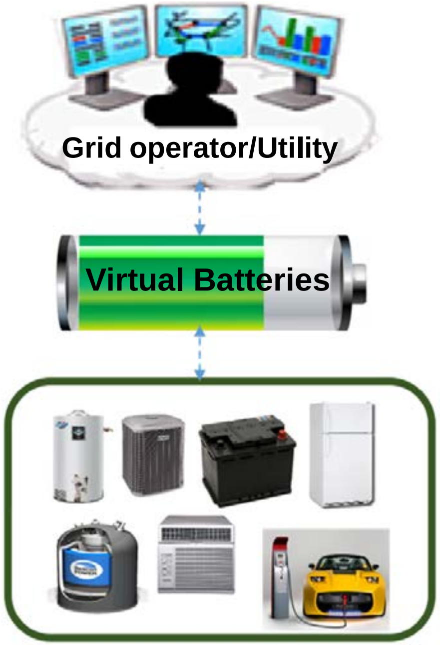
Team

- PNNL
  - Develop VB characterization, optimal schedule and device control method
  - Develop VB Assessment Tool (VBAT)
  - Perform cost-benefit analysis, validation, and testing
- ORNL
  - Provide experimental data from test sites and regional building load parameters for VBAT
  - Assist testing and validation
- NRECA
  - Integrate VB model and application assessment into Open Modeling Framework (OMF)
  - Outreach to its member utilities promoting VB technology and its applications
- University of Florida
  - Integrate medium-scale commercial buildings into VBAT and assist validation
- SCE
  - Testing and deployment

Challenge

- There is a growing need for **flexible assets from grid** due to increasing renewable generation
- Today's grid-scale energy storage systems require **high investment cost**
- Commercial and residential buildings can provide distributed **"virtual" battery capacity** complementing dedicated energy storage systems; need to be
  - **Identified**
  - **Quantified**
  - **Controlled**
- **Cost-benefit analysis** is required to determine potential return on investment and support decision-making





Grid operator/Utility

Virtual Batteries

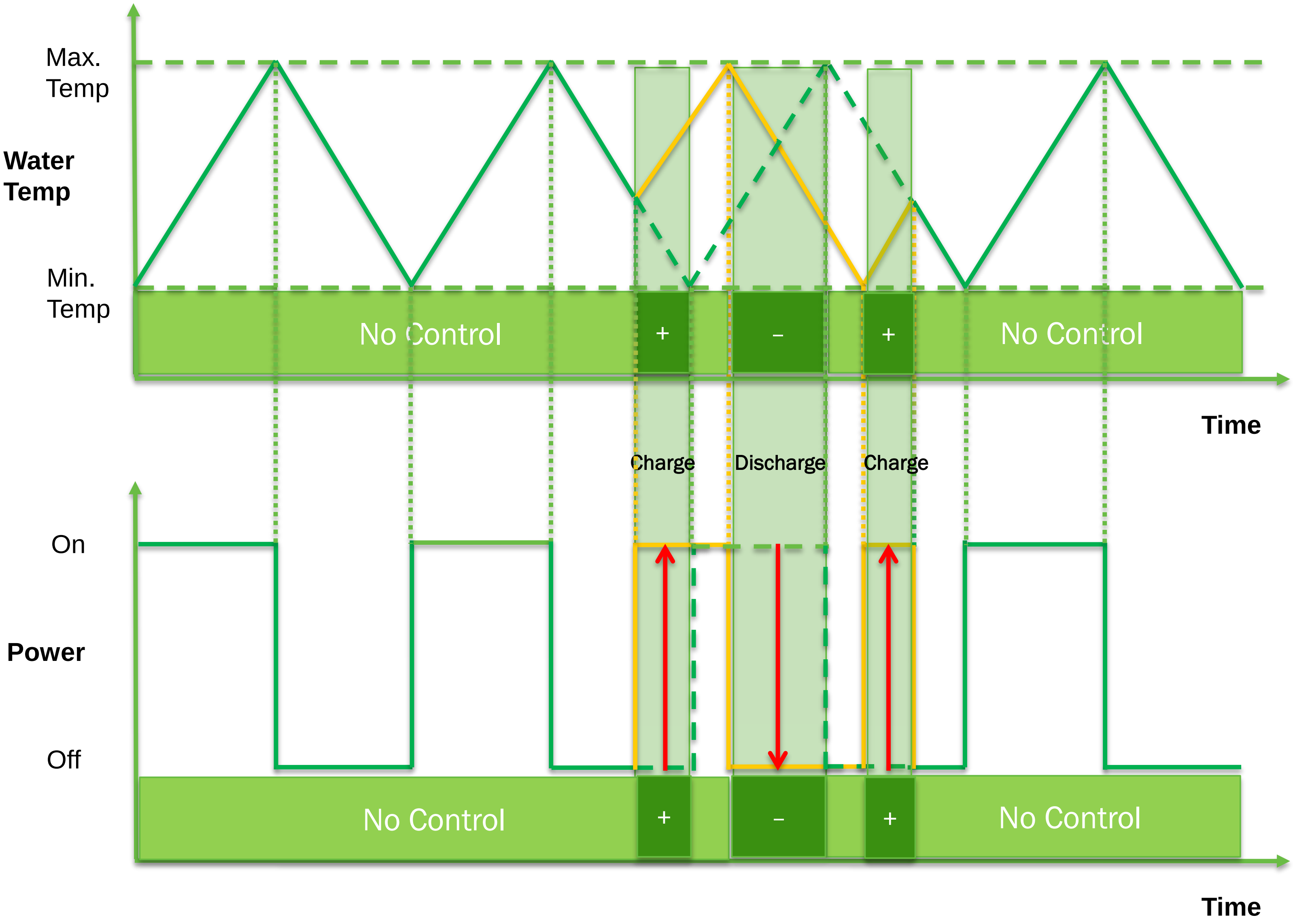
National Opportunity Assessment—VB Max. Tech

	Virtual Battery Assets	Power Potential (GW)*	Energy Potential (GWh)*	Current Investigation
1	Residential Air Conditioners and Heat Pumps	26.3	6.6	✓
2	Commercial HVAC with Roof Top Units	17.6	25.9	✓
3	Commercial HVAC with Air Handling Units	12.9	38.7	✓
4	Residential Water Heaters	10.6	10.6	✓
5	Refrigerators	4.3	2.2	
6	Residential Pool Pumps	4.7	4.7	
7	Commercial Water Heaters	1.0	1.0	
8	Electric Vehicles	0.8	1.6	
9	Super Markets and Grocery Stores	1.4	7.0	
10	Refrigerated Warehouses	0.3	0.6	
11	Data Centers	0.5	2.0	
12	Municipal Water Pumping	0.7	1.4	
	Total	**81.1**	**129.2**	

- Virtual battery resources could provide a maximum capacity of 81GW
- 20% of max capacity enough to meet additional 18GW intra-hour balancing requirements in 2020 scenario

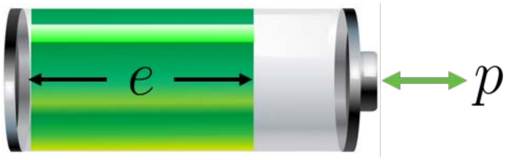
*peak load reduction study

Approach: VB Illustration—Water Heater



Approach: VB Battery Model

Representation for an aggregation of resources



VB dynamics:

$$\frac{de(t)}{dt} = -ae(t) + p(t)$$

P & E ranges:

$$P^{\min}(t) \leq p(t) \leq P^{\max}(t)$$
$$E^{\min}(t) \leq e(t) \leq E^{\max}(t)$$

Variable and parameters:

- $p(t)$ is the charging/discharging power
- $e(t)$ is the energy state
- $P^{\min}(t)$ and $P^{\max}(t)$ are the lower and upper power limits, respectively
- $E^{\min}(t)$ and $E^{\max}(t)$ are the its lower and upper energy limits, respectively
- a is the self-discharge rate

Developed a flexibility characterization method to estimate VB parameters given

- Resource type (residential air conditioners, water heaters, commercial HVAC, etc.)
- Number of resources
- Parameter values for the population (thermal resistance and capacitance, COP, etc.)
- External drivers such as ambient temperature, water draw, usage patterns, etc.

Approach: VB Characterization Method

A group of residential ACs as an example:

AC thermal dynamics model:

$$C^i \frac{d\theta^i(t)}{dt} = \frac{\theta_o - \theta^i(t)}{R^i} - \underbrace{s^i(t)P^i\mathrm{COP}^i}_{u^i(t)} + w^i(t);$$

- θ^i indoor air temperature
- θ_o is the outside temperature
- C^i thermal capacitance
- R^i thermal resistance
- s^i ON/OFF state
- P^i rated power
- COP^i coefficient of performance
- θ_r^i temperature setpoint
- Δ^i deadband
- w^i external disturbance

VB model:

Define

$$e^i(t) = C^i(\theta_r^i - \theta^i(t))/\mathrm{COP}^i$$
$$p^i(t) = u^i(t) - p^{\mathrm{base},i}(t)$$

where $p^{\mathrm{base},i}(t) = \frac{\theta_o(t) - \theta_r^i}{\mathrm{COP}^i R^i}$ and ignoring $w^i(t)$, yield

VB dynamics: $$\frac{de^i(t)}{dt} = -ae^i(t) + p^i(t)$$

where $a = \frac{1}{C^i R^i}$,

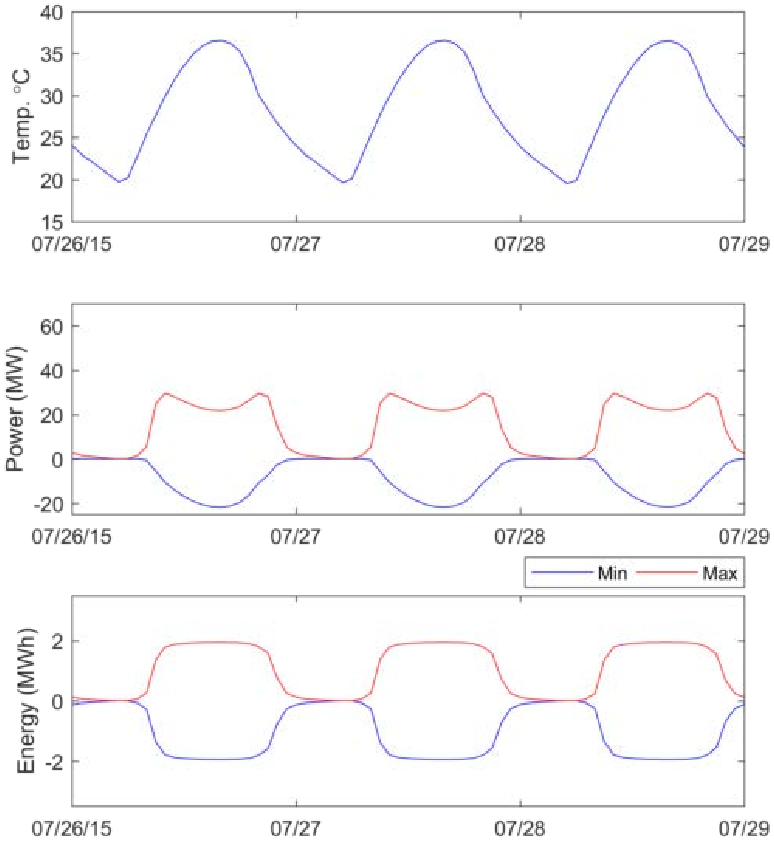
P & E ranges:

$$\underbrace{-p^{\mathrm{base},i}(t)}_{P^{\min}(t)} \leq p(t) \leq \underbrace{P^i - p^{\mathrm{base},i}(t)}_{P^{\max}(t)}$$

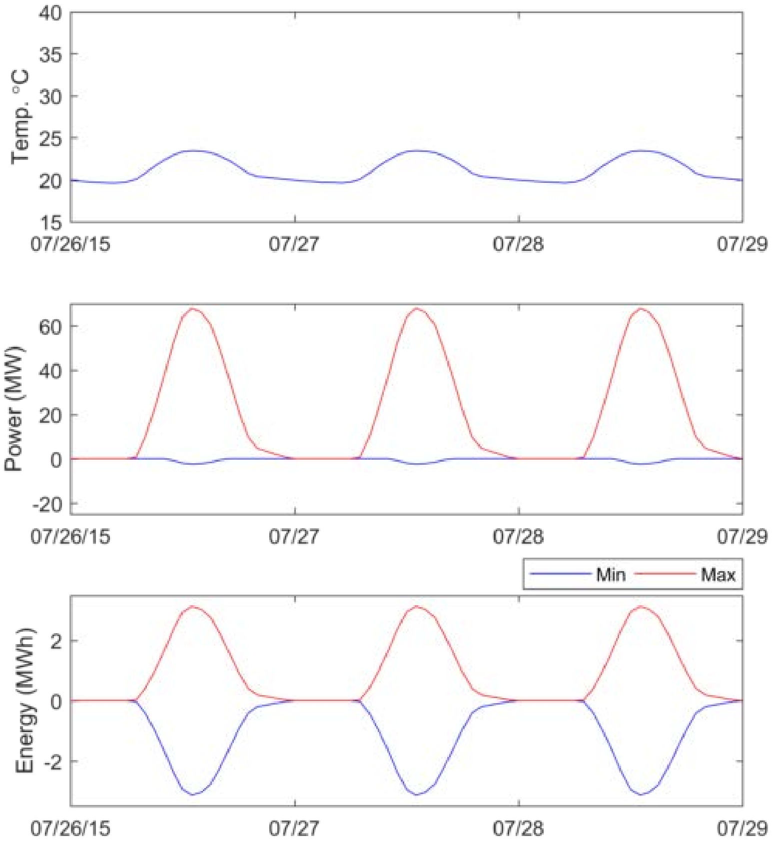
$$\underbrace{-\frac{C^i\Delta^i}{\mathrm{COP}^i}}_{E^{\min}(t)} \leq e(t) \leq \underbrace{\frac{C^i\Delta^i}{\mathrm{COP}^i}}_{E^{\max}(t)}$$

Approach: VB from Residential ACs at County Level

Siskiyou (8,000 ACs)



San Diego (280,000 ACs)



- Virtual battery potential varies based on outside temperature
- # of ACs available to participate in grid services varies based on outside air temperature
- Greater # of houses does not necessarily mean greater potential for grid services

Target Market and Impact of Project

Target Market: Grid operators and behind-the-meter asset owners/operators

Impact: Lower cost delivery of grid and end-user services by using behind-the meter virtual battery assets enabled by

- VBAT for planning study, providing building owners and utilities a means of quantifying technical potential and economic benefits of VB resources for end-user and/or grid services
- An operational tool to optimally schedule and control VB assets to provide different services
- Testing and validation in realistic environments to provide a quantifiable basis to compare VB resources and electrochemical storage for grid services

Progress: Project Status

FY16-17 (completed)

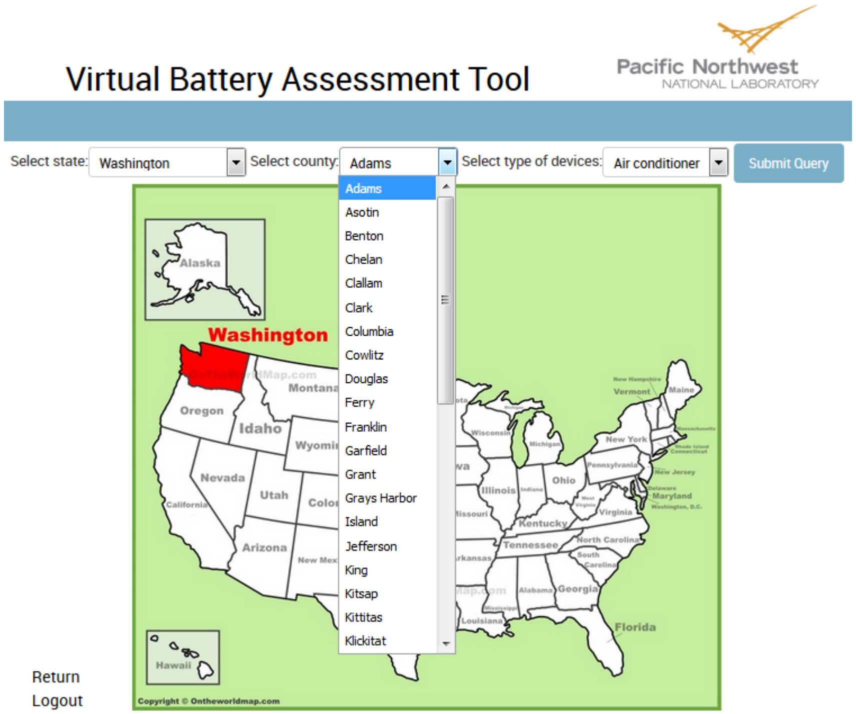
- Performed a national opportunity assessment to quantify the potential (GW/GWh) from building loads, Dec. 2016
- Developed virtual battery characterization methods, including both analytical and optimization based methods, Mar. 2017
- Completed a preliminary benefit assessment study for California, including revenue assessment and physical storage requirements, Aug. 2017

FY17-18 (in progress)

- Virtual Battery Assessment Tool, Feb. 2018
  - A database of VB potential from four residential TCLs at different geographical levels—county, state, region, and the U.S., completed.
  - A database of VB potential from medium-scale commercial buildings and commercial refrigeration, in progress.
- NRECA integration of VB model and assessment in OMF, Apr. 2018
  - VB potential assessment
  - VB economic benefit evaluation for behind-the-meter applications
- Development of locational net benefit analysis and case study using distribution systems within SCE

Progress: Virtual Battery Assessment Tool

- An interactive web application (http://35.162.145.49/index/)
- Assessment of VB potential from residential thermostatically controlled building loads at different geographical levels—county, state, census region, and U.S.
- Integration of medium-scale commercial buildings and commercial refrigeration models
- Customized assessment with user-defined inputs

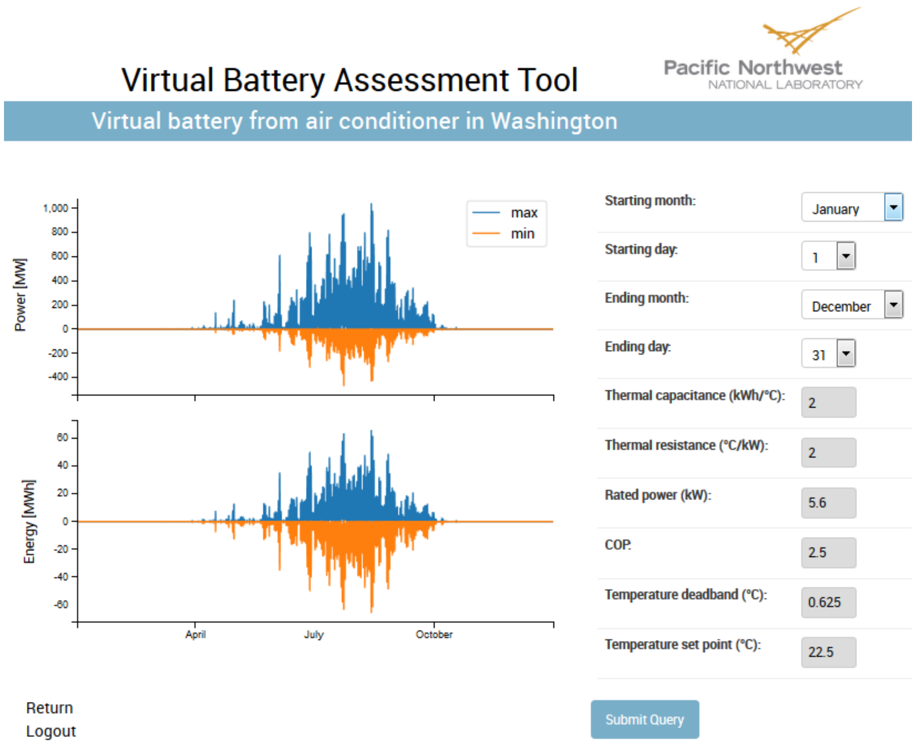


Virtual Battery Assessment Tool

Select state: Washington

Select county: Adams

Select type of devices: Air conditioner



Virtual Battery Assessment Tool

Virtual battery from air conditioner in Washington

Starting month: January

Starting day: 1

Ending month: December

Ending day: 31

Thermal capacitance (kWh/°C): 2

Thermal resistance (°C/kW): 2

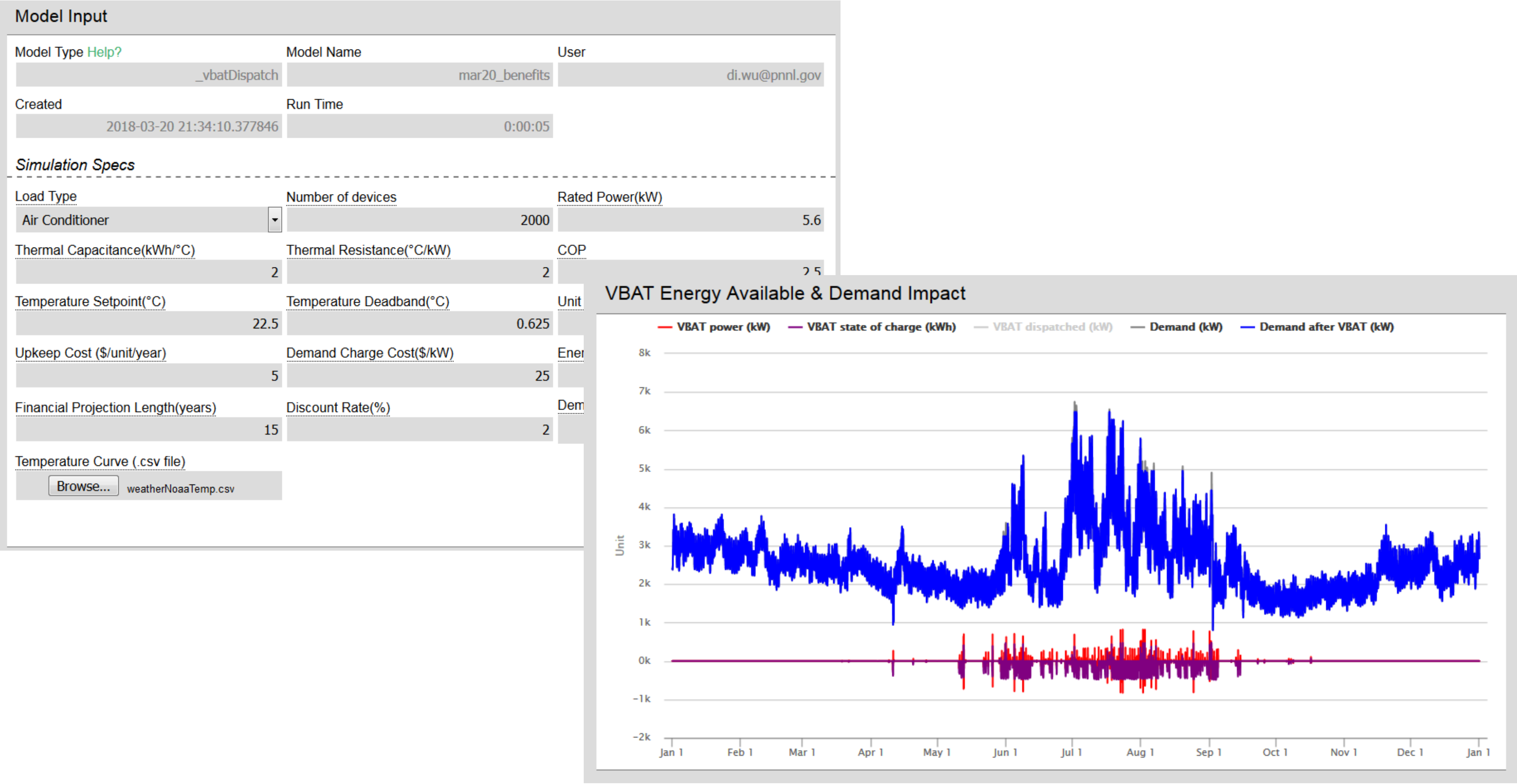
Rated power (kW): 5.6

COP: 2.5

Temperature deadband (°C): 0.625

Temperature set point (°C): 22.5

Progress: NRECA VB Assessment Study



Model Input

Model Type Help?
_vbatDispatch

Model Name
mar20_benefits

User
di.wu@pnnl.gov

Created
2018-03-20 21:34:10.377846

Run Time
0:00:05

Simulation Specs

Load Type
Air Conditioner

Number of devices
2000

Rated Power(kW)
5.6

Thermal Capacitance(kWh/°C)
2

Thermal Resistance(°C/kW)
2

COP
2.5

Temperature Setpoint(°C)
22.5

Temperature Deadband(°C)
0.625

Unit

Upkeep Cost ($/unit/year)
5

Demand Charge Cost($/kW)
25

Ener

Financial Projection Length(years)
15

Discount Rate(%)
2

Dem

Temperature Curve (.csv file)
Browse... weatherNoaaTemp.csv

VBAT Energy Available & Demand Impact

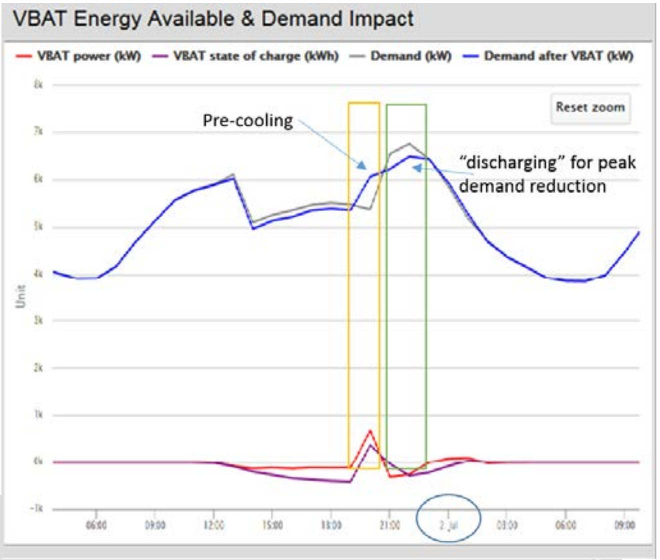
NRECA OMF links for VBAT Applications:

- https://www.omf.coop/newModel/_vbatEvaluation/FirstnameLastname
- https://www.omf.coop/newModel/_vbatDispatch/FirstnameLastname

Progress: NRECA VB Assessment Study (cont.)

$$\min_{d_j, e_k^{\mathrm{VB}}, p_k^{\mathrm{VB}}} \underbrace{\sum_{k=1}^{K} \lambda_k (L_k + p_k^{\mathrm{VB}}) \Delta T}_{\text{Energy Charge}} + \underbrace{\sum_{j=1}^{J} \beta_j d_j}_{\text{Demand Charge}}$$

$$\begin{array}{rll}
\text{subject to:} & & \\
\text{VB power limits:} & P_k^{\min} \le p_k^{\mathrm{VB}} \le P_k^{\max}, & \forall k = 1, \cdots, K \\
\text{Energy dynamics in VB:} & e_k^{\mathrm{VB}} = \alpha e_{k-1}^{\mathrm{VB}} + p_k^{\mathrm{VB}}, & \forall k = 1, \cdots, K \\
\text{VB energy limits:} & E_k^{\min} \le e_k^{\mathrm{batt}} \le E_k^{\max}, & \forall k = 1, \cdots, K \\
\text{Power demand:} & L_k + p_k \le d_j, \forall k \in \mathcal{N}_j & \forall j = 1, \cdots, J
\end{array}$$

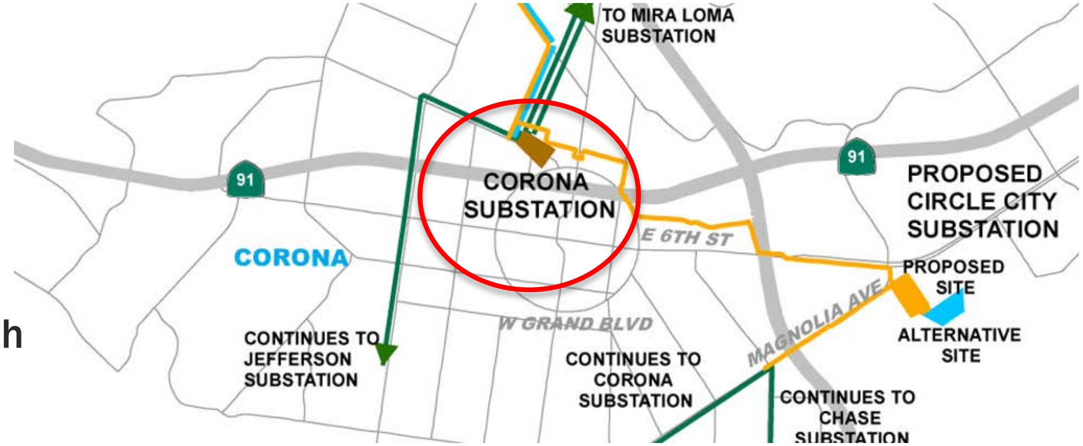

VBAT Energy Available & Demand Impact

Monthly Cost Comparison

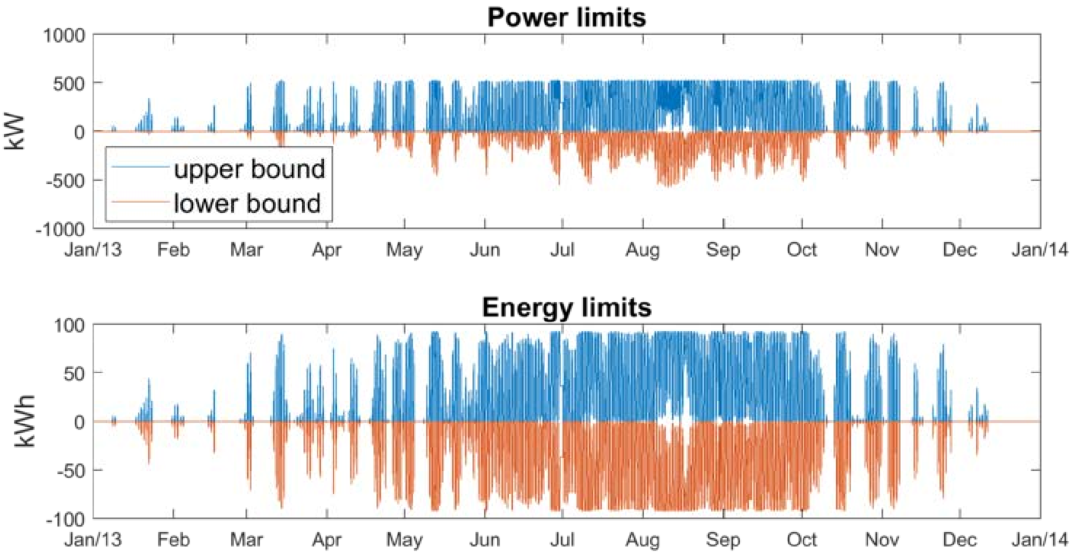
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Peak Demand (kW)	3,817	3,774	3,457	3,501	3,597	5,812	6,746	5,204	4,905	2,337	3,545	3,365
Adjusted Peak Demand (kW)	3,817	3,774	3,457	3,501	3,252	5,665	6,484	4,950	4,441	2,337	3,545	3,365
Energy (kWh)	2,192,216	1,819,984	1,841,376	1,606,514	1,546,322	1,993,841	2,951,885	2,435,934	1,533,820	1,304,142	1,590,647	1,846,676
Adjusted Energy (kWh)	2,192,216	1,819,984	1,841,376	1,606,514	1,545,129	1,993,613	2,950,375	2,432,501	1,533,505	1,304,142	1,590,647	1,846,676
Energy Cost ($)	131,533	109,199	110,483	96,391	92,779	119,630	177,113	146,156	92,029	78,249	95,439	110,801
Energy Cost using VBAT ($)	131,533	109,199	110,483	96,391	92,708	119,617	177,022	145,950	92,010	78,249	95,439	110,801
Demand Charge ($)	95,436	94,356	86,436	87,516	89,928	145,296	168,660	130,104	122,616	58,428	88,632	84,132
Demand Charge using VBAT ($)	95,436	94,356	86,436	87,516	81,301	141,616	162,096	123,744	111,036	58,428	88,632	84,132
Total Cost ($)	226,969	203,555	196,919	183,907	182,707	264,926	345,773	276,260	214,645	136,677	184,071	194,933
Total Cost using VBAT ($)	226,969	203,555	196,919	183,907	174,008	261,233	339,118	269,694	203,046	136,677	184,071	194,933
Savings ($)	0	0	0	0	8,699	3,694	6,655	6,566	11,599	0	0	0

Progress: SCE Feeder Benefit Analysis

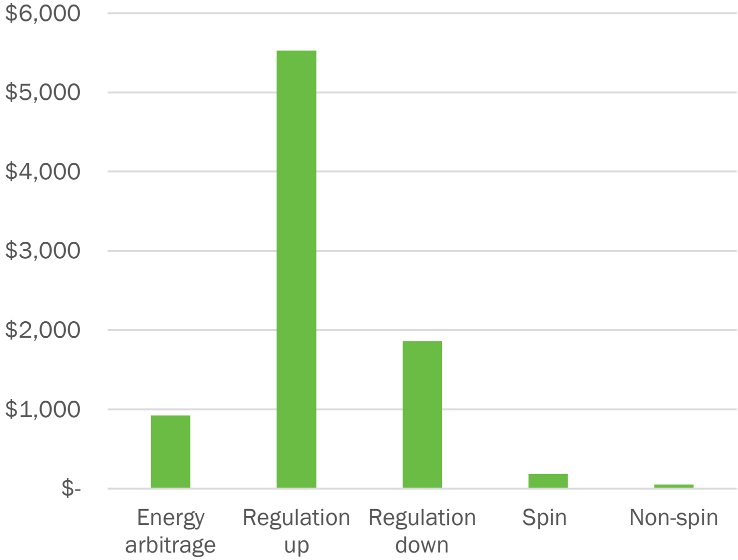
- Circuit name: PIRCE (under CORONA substation)
- Primary voltage: 12.47 kV
- Circuit length: 8.6 miles
- Preliminary load: 23.5 MVA
- Residential house: 340 (152 with electric air conditioning)



VB Potential



Annual Benefits



Stakeholder Engagement

- PNNL and NRECA have worked with utility members within NRECA to study VB potential and benefits in their systems
  - VB assessment tool integrated into OMF to enable their utility members to perform techno-economic assessment of building loads as VB
  - Project presented at NRECA TechAdvantage Conference, which attracts utilities, co-op vendors, and industry leaders
  - Collaboration with co-ops to demonstrate and validate VB method
    - Allegheny Electric Cooperative
    - Flathead Electric Cooperative
    - Oklahoma Electric Cooperative
    - Central Alabama Electric Cooperative
    - Washington Electric Coop (Vermont)
- PNNL has worked with one of our utility partners, Southern California Edison, to perform analysis on VB flexibility and economic benefits for selected feeders in their system
- The project team will work with stakeholders for field work and testing of optimal scheduling and device control of VB technology.

Remaining Project Work: Planned Activities

- Work with ORNL to perform assessment of regional VB potential from medium-scale commercial buildings and commercial refrigeration
- Continue outreach efforts to NRECA utility members and co-ops
  - Design and test control algorithms for residential assets with NRECA
- Continue the net benefit analysis with SCE
- Work with ORNL to develop and test control algorithms for selected commercial building loads and refrigeration systems

Thank You

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REFERENCE SLIDES

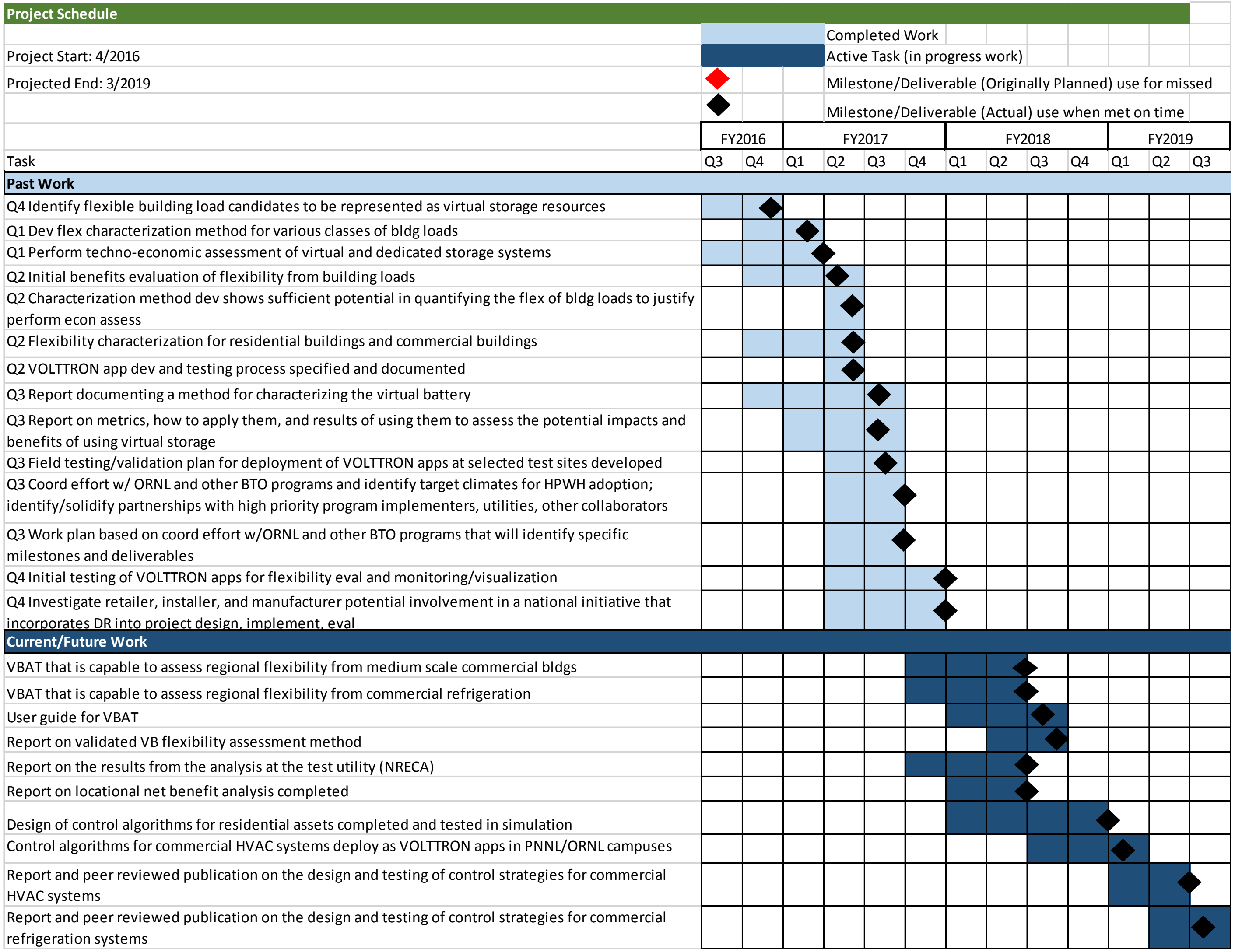
Project Budget

Project Budget: $3M
Variances: None.
Cost to Date: As of 3/2018, expenditures total $1.7M.
Additional Funding: None.

Budget History					
4/2016– FY 2017 (past)		FY 2018 (current)		FY 2019 – 3/2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$1.2M	$0	$1.3M	$0	$.5M	$0

Project Plan and Schedule

- Project began in 4/2016, with field testing and validation scheduled for completion in 4/2019.
- Go/No-Go: VBAT and regional VB potential from building loads in the U.S. (2/2018)



Project Schedule

Project Start: 4/2016

Projected End: 3/2019

▒ 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	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Past Work													
Q4 Identify flexible building load candidates to be represented as virtual storage resources	▒	◆											
Q1 Dev flex characterization method for various classes of bldg loads		▒	◆										
Q1 Perform techno-economic assessment of virtual and dedicated storage systems	▒	▒	◆										
Q2 Initial benefits evaluation of flexibility from building loads		▒	▒	▒ ◆									
Q2 Characterization method dev shows sufficient potential in quantifying the flex of bldg loads to justify perform econ assess				▒ ◆									
Q2 Flexibility characterization for residential buildings and commercial buildings		▒	▒	▒ ◆									
Q2 VOLTTRON app dev and testing process specified and documented				▒ ◆									
Q3 Report documenting a method for characterizing the virtual battery		▒	▒	▒	▒ ◆								
Q3 Report on metrics, how to apply them, and results of using them to assess the potential impacts and benefits of using virtual storage			▒	▒	▒ ◆								
Q3 Field testing/validation plan for deployment of VOLTTRON apps at selected test sites developed				▒	▒ ◆								
Q3 Coord effort w/ ORNL and other BTO programs and identify target climates for HPWH adoption; identify/solidify partnerships with high priority program implementers, utilities, other collaborators				▒	▒ ◆								
Q3 Work plan based on coord effort w/ORNL and other BTO programs that will identify specific milestones and deliverables				▒	▒ ◆								
Q4 Initial testing of VOLTTRON apps for flexibility eval and monitoring/visualization				▒	▒	▒ ◆							
Q4 Investigate retailer, installer, and manufacturer potential involvement in a national initiative that incorporates DR into project design, implement, eval				▒	▒	▒ ◆							
Current/Future Work													
VBAT that is capable to assess regional flexibility from medium scale commercial bldgs						█	█	█ ◆					
VBAT that is capable to assess regional flexibility from commercial refrigeration						█	█	█ ◆					
User guide for VBAT							█	█	█ ◆				
Report on validated VB flexibility assessment method								█	█ ◆				
Report on the results from the analysis at the test utility (NRECA)						█	█	█ ◆					
Report on locational net benefit analysis completed							█	█ ◆					
Design of control algorithms for residential assets completed and tested in simulation							█	█	█	█ ◆			
Control algorithms for commercial HVAC systems deploy as VOLTTRON apps in PNNL/ORNL campuses									█	█	█ ◆		
Report and peer reviewed publication on the design and testing of control strategies for commercial HVAC systems											█	█ ◆	
Report and peer reviewed publication on the design and testing of control strategies for commercial refrigeration systems												█	█ ◆