Grid Architecture

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

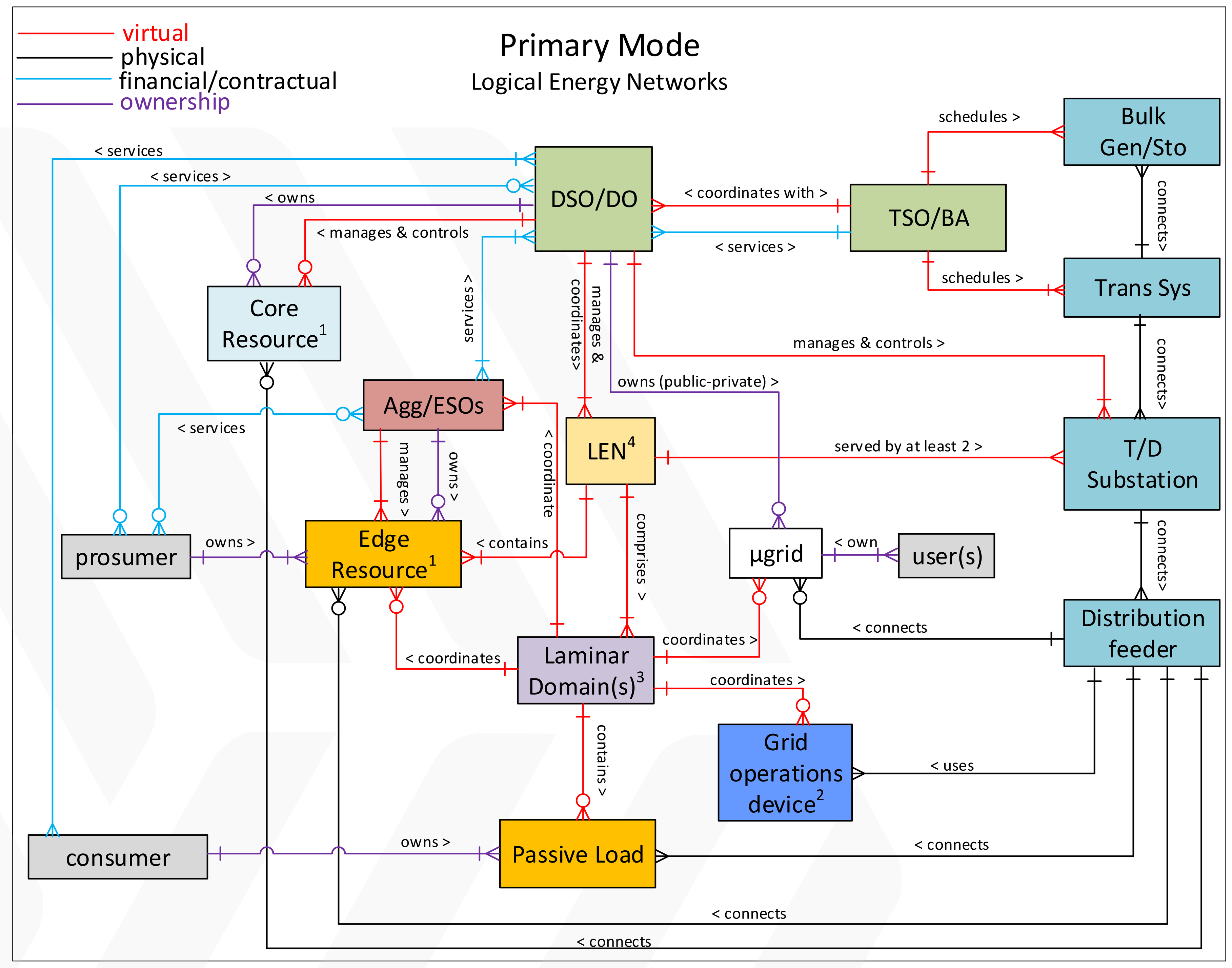
Project Description

Grid architecture is the application of system architecture, network theory, and related disciplines to the whole electric grid. The purpose of this project is to re-shape the grid, remove essential barriers to modernization, redefine key grid structures, and identify securable interfaces and platforms.

Expected Outcomes

- Provide five reference architectures that show how to relieve essential constraints that impede grid modernization and how to define grid structures that provide resilience, new functionality, security, and interoperability
- Provide tools and methods to adapt the reference architectures to specific utilities
- Proper structure (architecture) future-proofs grid modernization investments; poor structure results in high costs and low performance

Significant Milestones	Date
Architecture Initialization	10/2016
Reference Model Development	10/2016
Component/Interface Model Development	4/2017
Architecture Development	12/2018
Architecture Validation	4/2019
Architecture Completion	4/2019



High Resilience Grid Architecture

Progress to Date (Example Innovations)

- Electric Grid Resilience and Reliability for Grid Architecture
- Practical Theory of Grid Resilience
- Distribution Storage Networks
- Logical Energy Networks and Distribution Virtualization
- Sensing and Measurement Architecture for Grid Modernization
- Electricity Market Structure & Components Models
- Advanced Networking Paradigms for High-DER Distribution Grids
- Comparative Architecture Analysis
- Architectural Basis for Highly Distributed Transactive Power Grids
- A Mathematical Representation of System Architectures

www.gridarchitecture.pnnl.gov

Vermont Regional Partnership: Facilitating the Effective Expansion of Distributed Energy Resources

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

GMLC 1.3.10 PI: Robert Broderick (SANDIA); Plus 1: Mark Ruth (NREL)

Utility Partners

GREEN MOUNTAIN POWER
VERMONT ELECTRIC CO OP INC
Vermont Electric Power Company VELCO

University Partners

The UNIVERSITY of VERMONT
Georgia Tech

Project Description & Objective

Developed an optimal and replicable approach to distributed energy resource (DER) integration at the distribution level to meet the state's goal of 90% renewable energy penetration by 2050. Key insights from what we learned in Vermont can be applied to the rest of the nation.

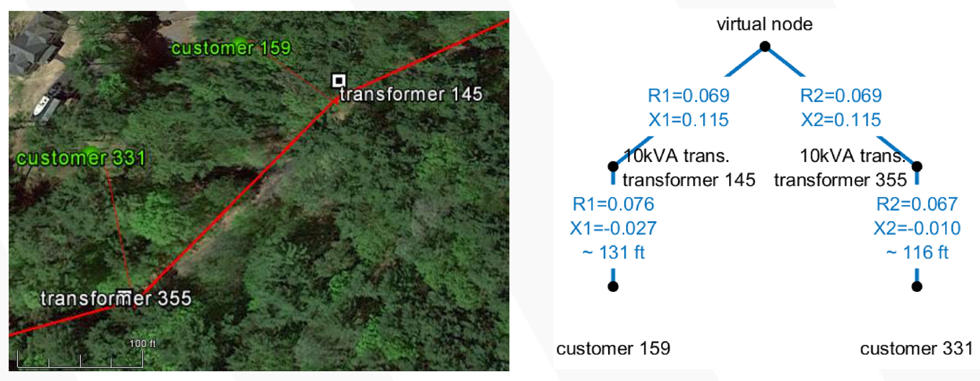
Final Project Outcomes

1. Showed how to achieve high levels of DER integration without causing negative impacts to the distribution system
2. Developed a replicable approach for DER integration at the distribution level in each of the three task areas
3. Disseminated the results and could replicate methodology for other stakeholders

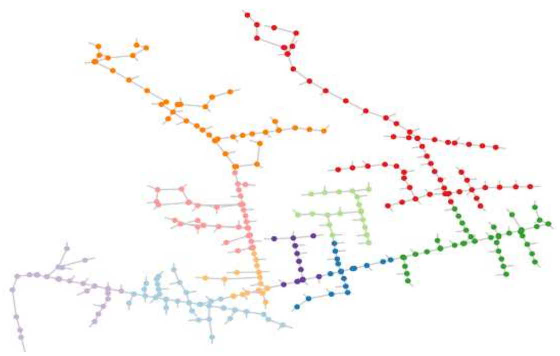
Final Project Deliverables	Date
Task 1 – DER integration Received 14 distribution models, AMI data and controller data. Secondary system parameter estimation for 3 feeders Phase identification testing on 1 feeder Hosting capacity analysis performed on 14 feeders Optimal siting of energy storage on 1 feeder	11/2017
Task 2– DER control Formulated network model and developed preliminary optimization algorithms. Grid LAB-D models, populated with residential ES system models, running in IESM. Updated algorithms after analysis and simulation. Ability to control residential ES systems from aggregator module within IESM demonstrated.	11/2017
Task 3– DER Forecast Provided 3 areas for improvement of the VTWAC forecasts.	11/2017

Task #1: DER Integration and Modeling

Improve distribution system models through innovative parameter estimation methods and use them to determine optimal amount and placement of photovoltaic (PV) solar and battery storage



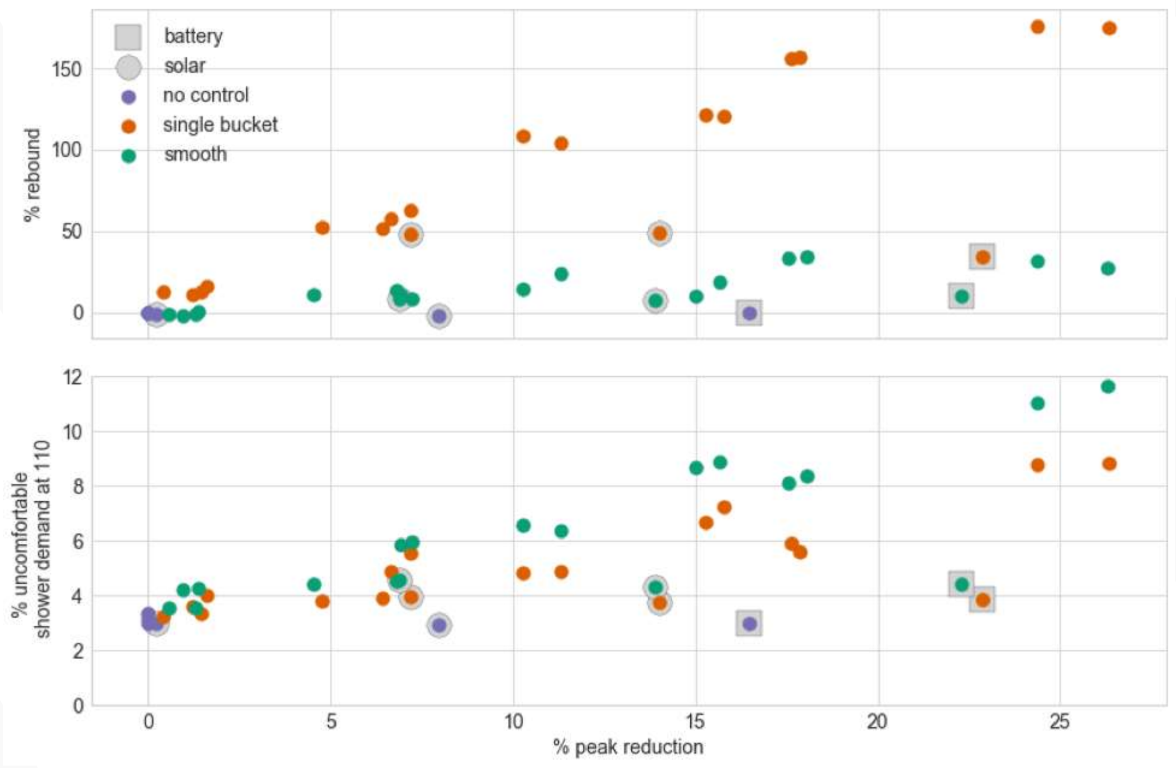
Secondary circuit parameter and topology estimation on 3 feeders.



Developed circuit reduction methods for energy storage optimization

Task #2: DER Control & Optimization

Develop and validate new control strategies for managing demand response rebound effects



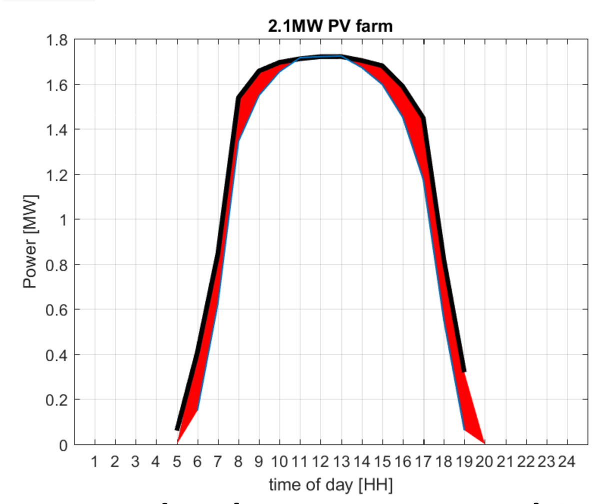
Developed a new electric water heater control strategy and validated it on two Green Mountain Power feeders (ER-51 & 9G2) via simulation.

The new strategy reduced the rebound from >150% of peak to ≈30% while only increasing the number of customers experiencing discomfort (demanding hot water when the temperature is under 110°F) from 9% to 12%.

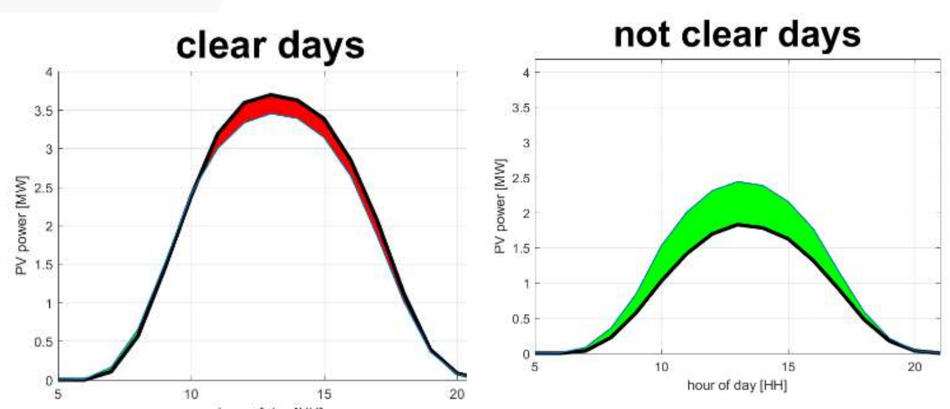
Task #3: DER Forecasting

Improvements to the solar forecasting to improve general predictions and system management. Identified three:

- Account for azimuth of PV modules
- Faster adjustments to changes in distributed PV capacity
- Separate forecast training on clear vs. cloudy days



Capture dual axis tracking and module azimuth



Separate forecast training on clear and cloudy days

Clean Energy and Transactive Campus Project (CETC)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

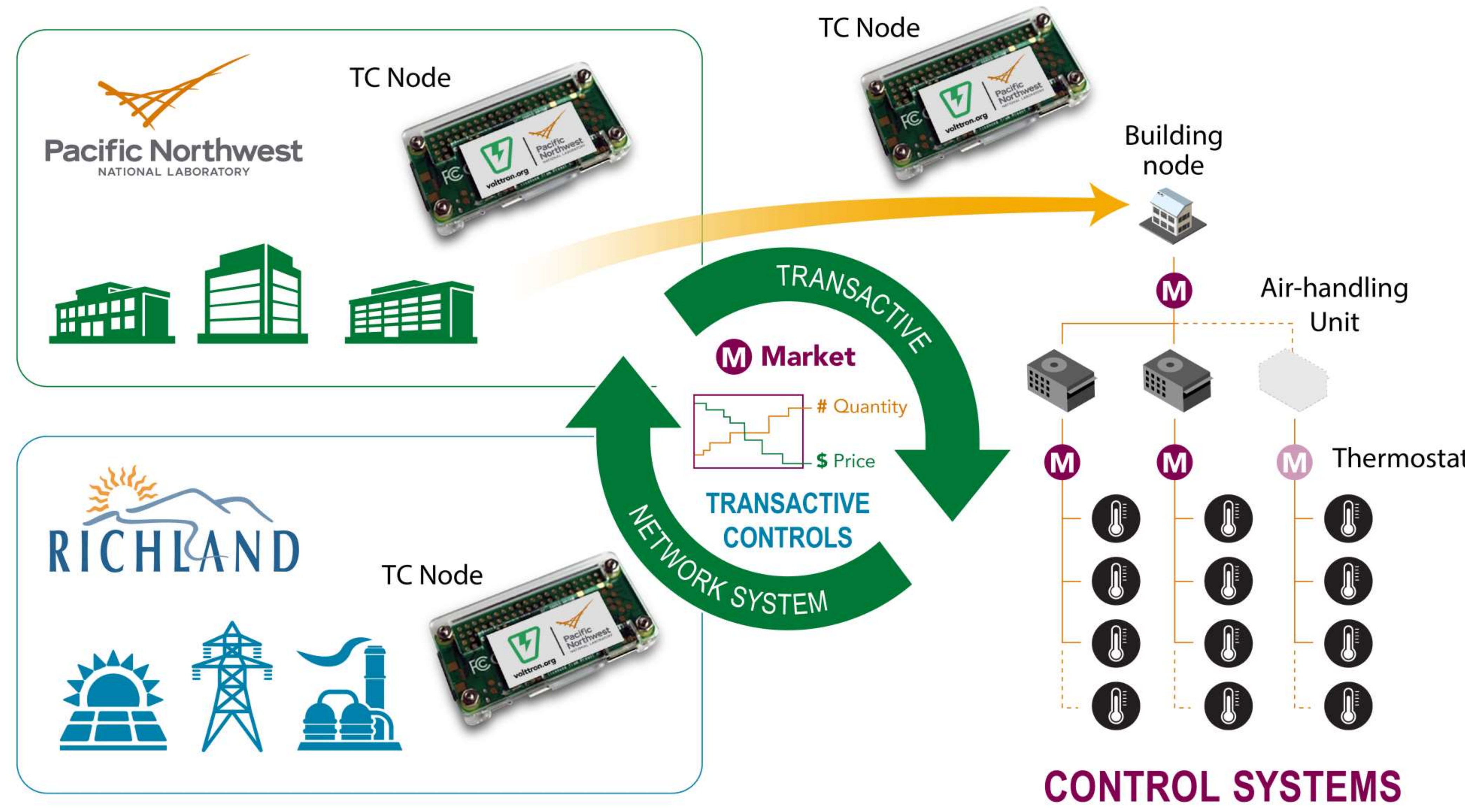
Project Description

CETC is a multi-campus effort that's conducting research and development (R&D) to advance commercial building energy efficiency and transactive control of distributed energy resources.

Expected Outcomes

- A replication "recipe" for broadly extending transactive control to buildings, campuses, and districts to help address increased deployments of clean energy technologies and aging infrastructures
- Technologies/tools that enable scalability of methods
- A clean energy and responsive building load R&D infrastructure in Washington State
- Contributions to goals of the DOE Building Technologies Office, Grid Modernization Laboratory Consortium and Grid Modernization Initiative
- **Ultimately, enhanced power grid reliability, energy efficiency, renewable energy integration, and cost savings**

Significant Milestones	Date
Design, develop and deploy infrastructure to support multi-campus experiments – complete	5/30/17
Multi-campus integration and testing – complete	9/30/17
Development and testing of algorithms that provide transactive control services – on track	12/31/18



A Transactive Network System, as designed in CETC, coordinates energy markets, the city utility, and operation of Pacific Northwest National Laboratory (PNNL) buildings and their devices, such as air-handling units.

Progress to Date

- Transactive control and energy efficiency experiments designed, deployed and validated in PNNL campus buildings
  - 8 journal papers, 4 technical reports, and 2 user guides
- Intelligent Load Control tool developed for peak load management, capacity bidding, and transactive energy systems applications
- Key advances made in transactive control and coordination methods and fault detection and diagnostics
- PNNL ready to initiate coordination of multiple buildings with a signal from the local utility
- Recruitment of Case Western Reserve University and University of Toledo to replicate key aspects of the control methodologies on their campuses

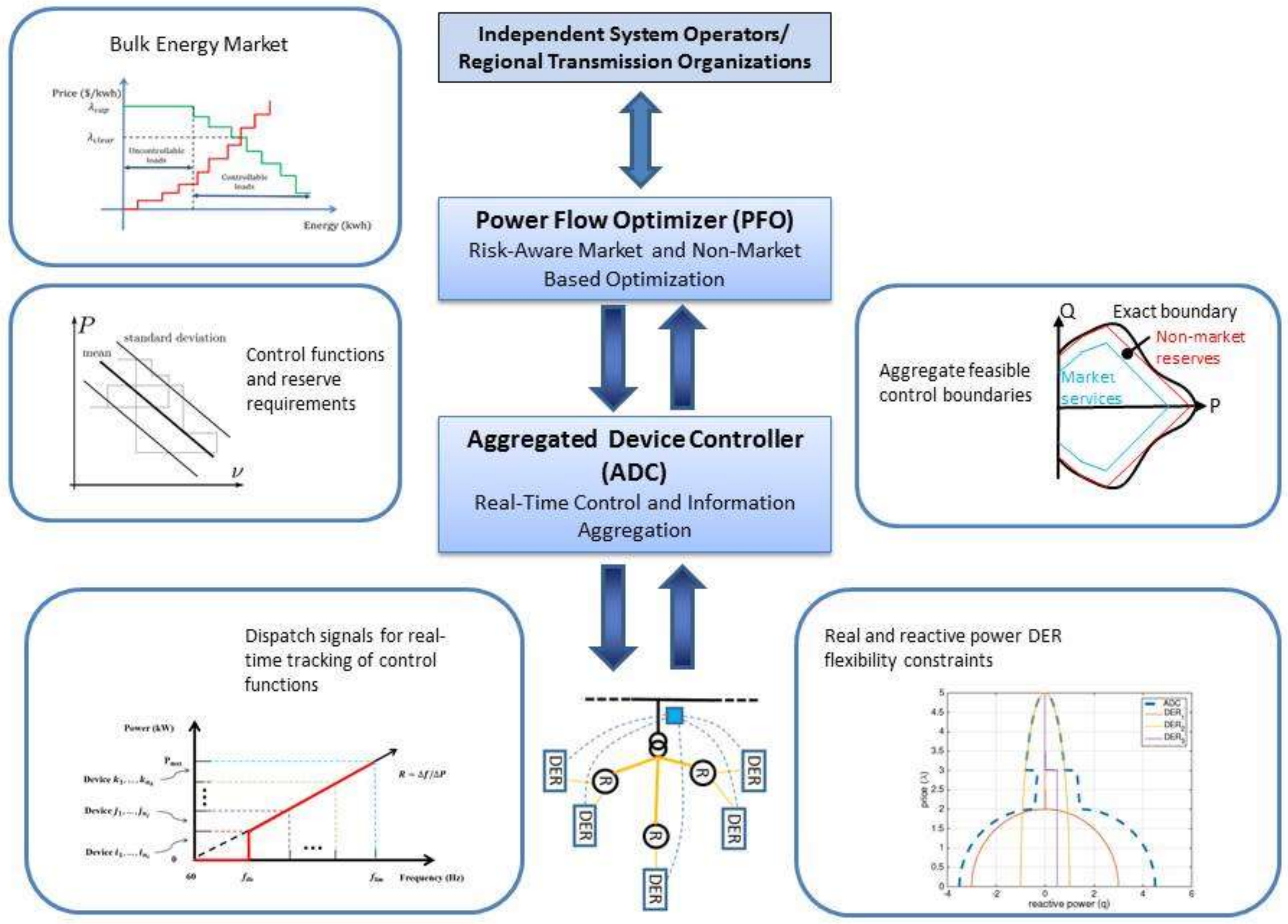
GMLC 1.4.10: Control Theory

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

The focus of this project is to develop new integrated optimization and control solutions, including architectures, algorithms, and deployment strategies for the U.S. power grid. This effort will support the GMLC multi-year program plan vision for transitioning the power grid to a state where a huge number of distributed energy resources (DERs) are participating in grid control. The specific objectives of the project are to:

- Ensure architectural compatibility of control theory and solutions.
- Coordinate and control diverse DERs (>10,000) with widely different responses.
- Incorporate power flow physics and network constraints into control solutions.
- Systematically manage uncertainty from intermittent generation and large number of controlled DERs.
- Integrate with legacy and bulk power system markets.



Interfaces for PFO and ADC systems

Expected Outcomes

- Integrated optimization and control systems that are more effective at maintaining operating margins.
- A 33% decrease in cost of reserve margins while maintaining reliability by 2025.
- Interconnection of intermittent power generation with less need for electrical storage and lower integration costs.

Significant Milestones	Date
Documented architectural reference models for control	11/1/2016
Completed integrated optimization and control theory roadmap	11/1/2016
Documented real-time control strategies for providing ancillary services from aggregated DERs	10/1/2017
Completed risk-aware control of ~10,000 DERs	4/1/2019

Progress to Date

- Completed a comprehensive integrated optimization and control theory roadmap consisting of (i) control system architectures, (ii) Power Flow relaxations and approximations, (iii) DER aggregation and flexibility domains, and (iv) strategies for real-time DER control, risk-aware power flow optimization.
- Validated architecture and development roadmap, and progress with Industry Advisory Board.
- Completed preliminary testing of each individual algorithm – load aggregation, real-time DER control and power flow optimization.
- Completed initial set-up for numerical test-bed.
- 43 conference and journal submissions

1.4.11 Multi-Scale Integration of Control Systems (EMS/DMS/BMS Integration)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

This project aims to create an integrated grid management framework for the end-to-end power delivery system – from central and distributed energy resources at bulk power systems and distribution systems, to local control systems for energy networks, including building management systems. Key tasks are:

- Use case development
- Open framework development for EMS/DMS/BEMS integration
- Integration of new stochastic applications into EMS operations
- Demonstration of EMS/DMS/BMS Integration

Expected Outcomes

- An platform linking EMS, DMS, and BMS operations, and being the ***FIRST*** in the national lab complex to demonstrate EMS/DMS/BMS interactions on industry test systems.
- New transformative operations applications (stochastic operations and forecasting data integration and decision support) that transform or extend existing EMS applications.

Significant Milestones	Date
Y1 Annual Milestones: Completed the use case report and data exchange requirements/protocols report. Completed integration of LANL ED, SNL UC engine and ANL's renewable forecasting.	3/30/2017
Y2 Annual Milestones: Demonstrated integration of DMS and BMS information on the use cased; Established the connection between EMS at PNNL and DMS at NREL.	3/30/2018
Y3 Annual Milestones: Successfully demonstrate integrated EMS/DMS/BMS platform; Demonstrate the uncertainty modeling and forecasting method in the integrated EMS/DMS/BMS system.	3/30/2019

National Lab Team: Liang Min and Philip Top/LLNL, Mark Rice and Emily Barrett/PNNL, Yingchen Zhang and Rui Yang/NREL, Bryan Arguello /SNL, Sidhant Misra/LANL, and Zhi Zhou/ANL

Partner: Anjan Bose/WSU

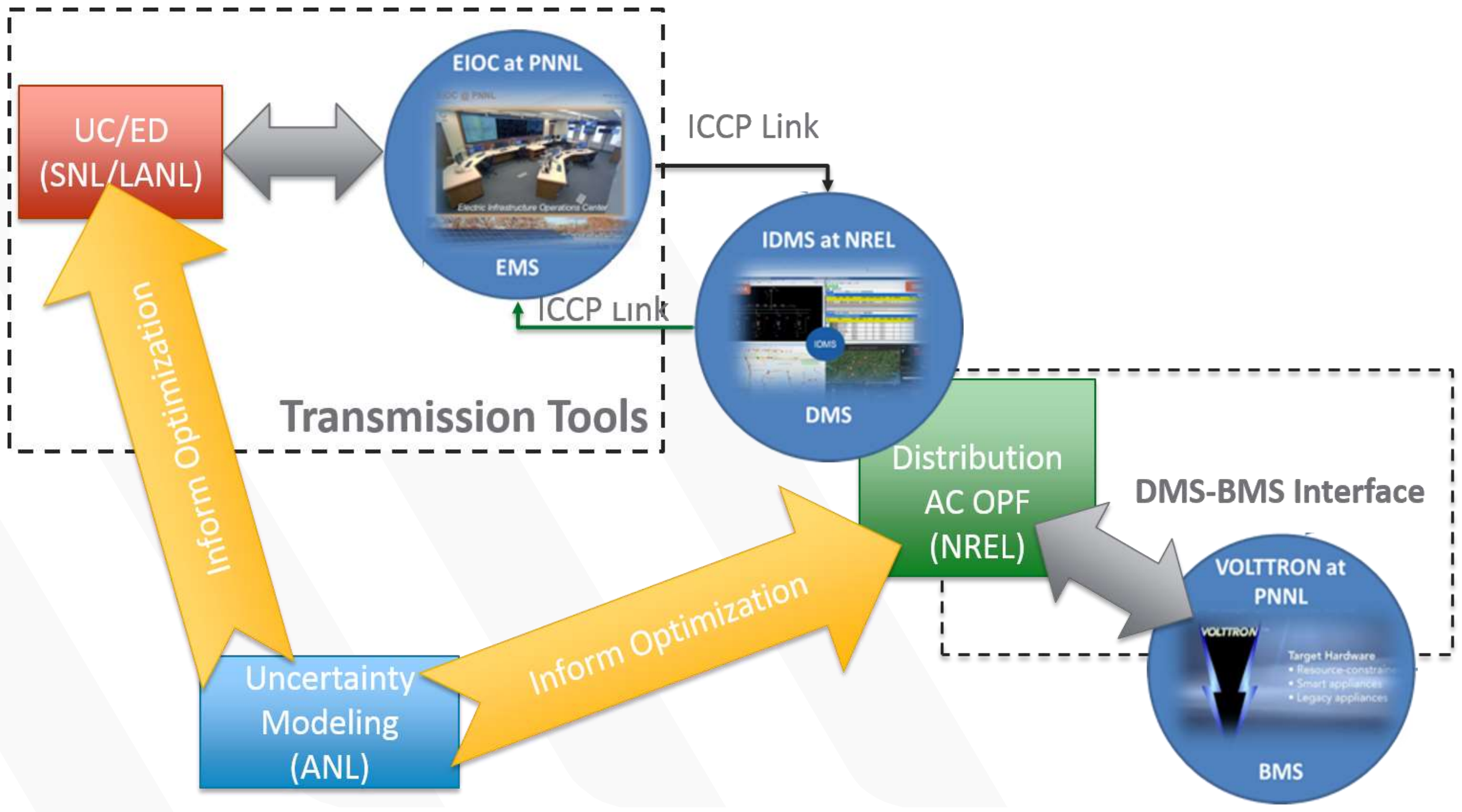


Figure 1 EMS/DMS/BMS System Architecture

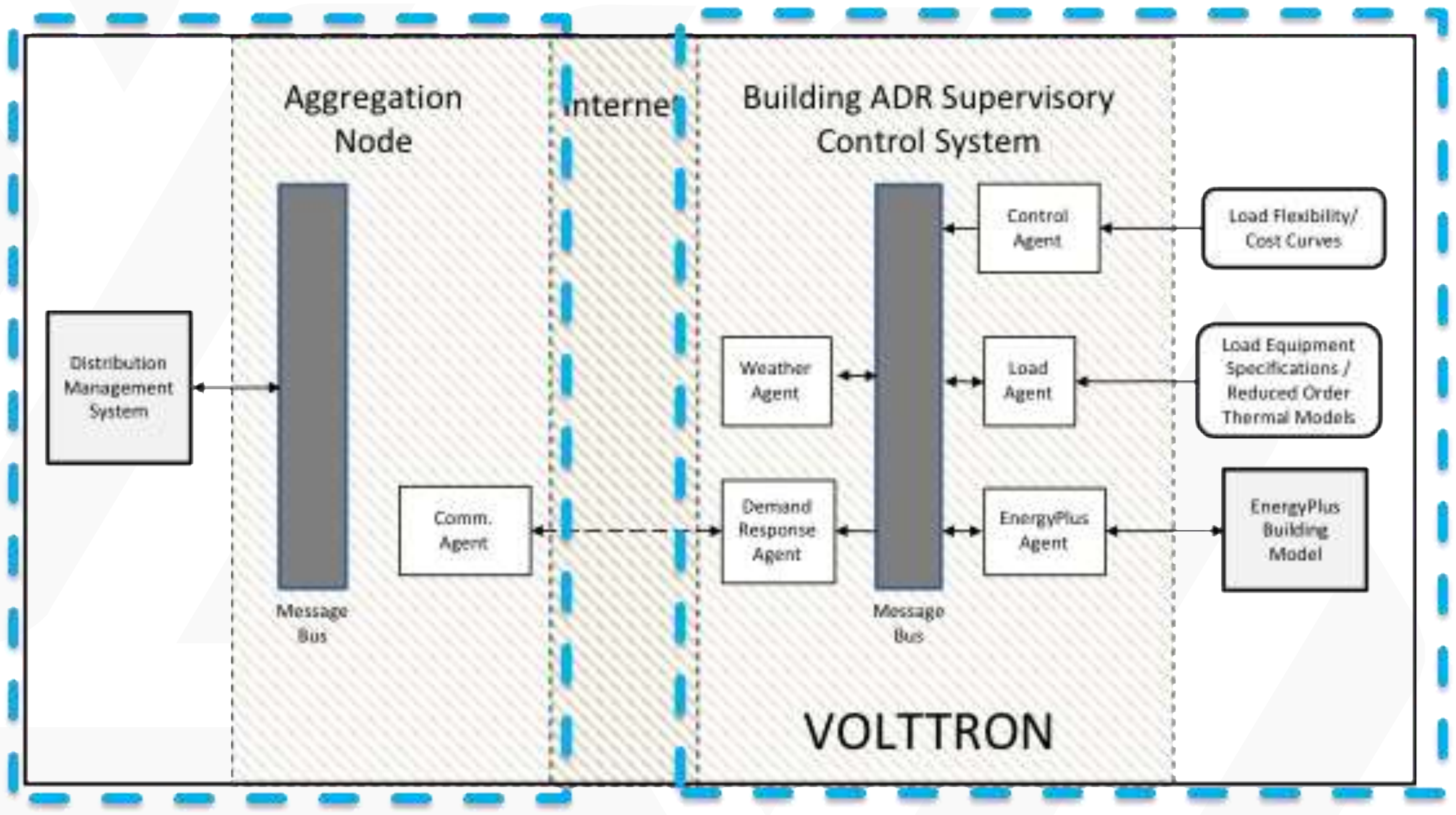


Figure 2 EMS/DMS/BMS System Architecture

Progress to Date

- **Year 1** - Completed the use case report and data exchange requirements/protocols report (12/2/2016); completed the integration of stochastic UC/ED/forecasting (3/30/2017).
- **Year 2** - Demonstrated the integration of DMS and BMS information on the use case (3/30/2018); Established the link between EMS and DMS (6/30/2018).

Workshops or other stakeholder engagement

- Presented at the advanced Distribution Management System (ADMS) Industry Steering workshops 2016 and 2017.
- Presented at IEEE Innovative Smart Grid Technologies ADMS panels, 2016, 2017 and 2018.
- Proposed to be on the panel for the IEEE General Meeting TSO-DSO panel 2019.

Virtual Battery-Based Characterization and Control of Flexible Building Loads Using VOLTTRON™

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

While grid-scale energy storage technologies rapidly improve, they still require considerable capital investment. Existing residential and commercial building infrastructure, such as water heaters and air conditioning systems, might provide distributed “virtual storage” at a much lower first cost. This project is identifying, quantifying, and assessing the difficulty of controlling virtual storage assets to complement grid-scale physical energy storage systems.

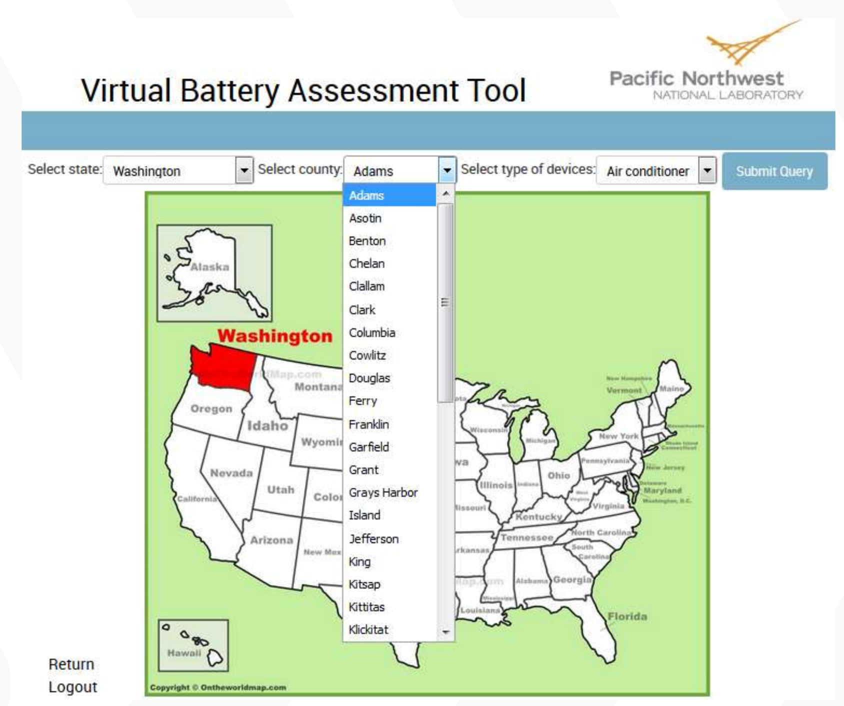
Expected Outcomes

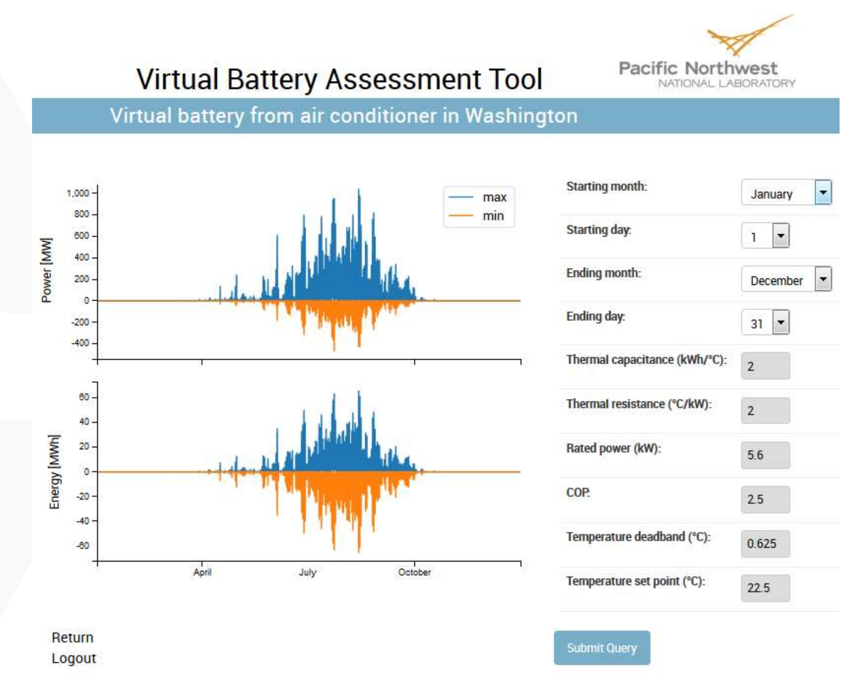
- Utilities and building owners can use flexible building loads as virtual batteries to provide grid and end-user services
- Integration of more renewable generation, such as wind and photovoltaics, into power systems
- Improved building operational efficiency

Significant Milestones	Date
Flexibility characterization method for residential and commercial buildings - complete	3/17
Virtual Battery Assessment Tool and regional VB potential from building loads in the U.S. - complete	2/18
Field testing and validation; documentation of results - on track	12/18

Progress to Date

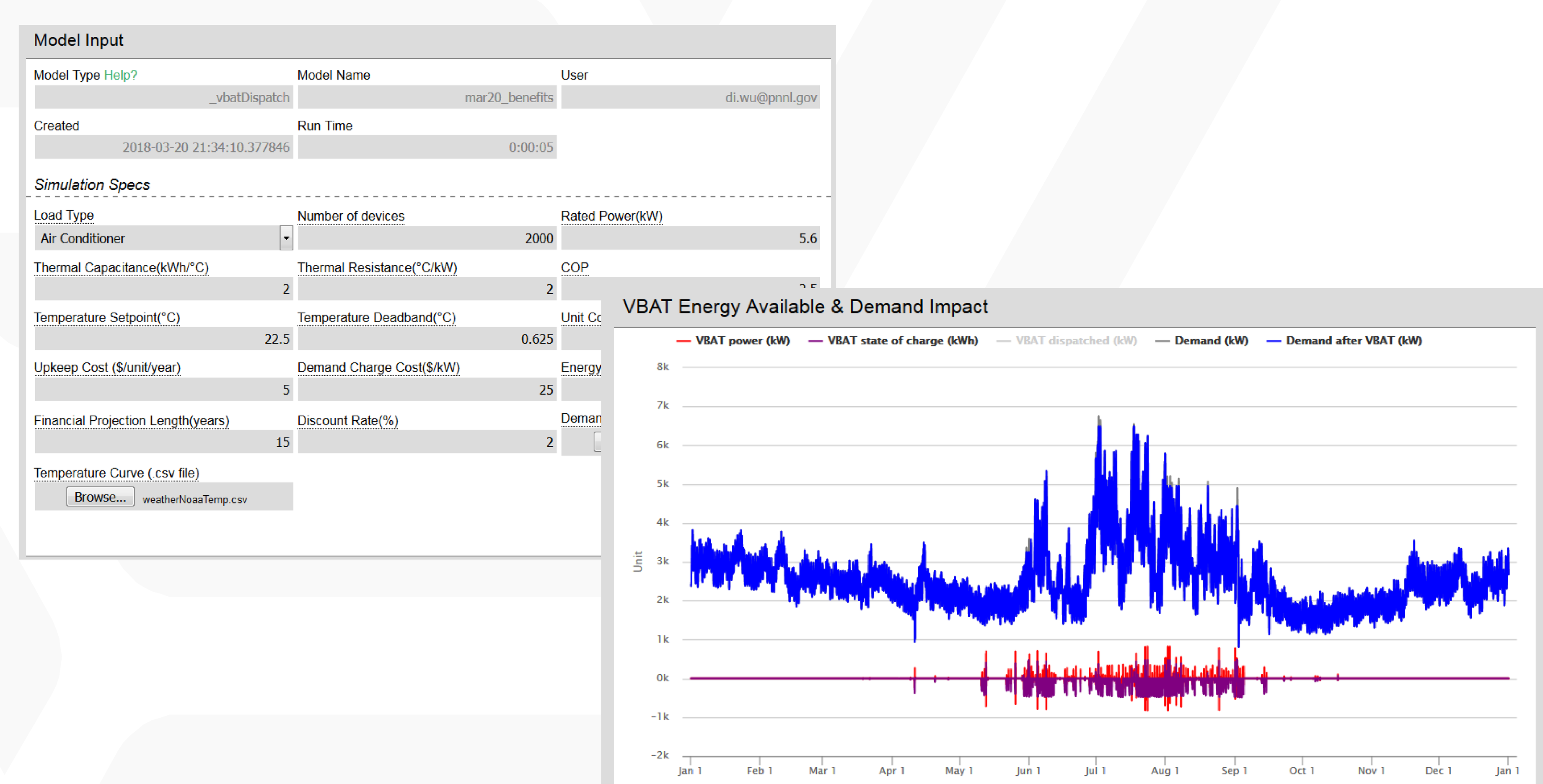
- Performed national opportunity assessment to quantify potential virtual storage resource
- Completed development of Virtual Battery (VB) tool (http://35.162.145.49/index/)





- Worked with NRECA to integrate VB model and assessment in Open Modeling Framework (OMF)

NRECA OMF links for VBAT Applications:
https://www.omf.coop/newModel/_vbatEvaluation/FirstnameLastname
https://www.omf.coop/newModel/_vbatDispatch/FirstnameLastname



- Completed locational net benefit analysis using distribution systems for Southern California Edison

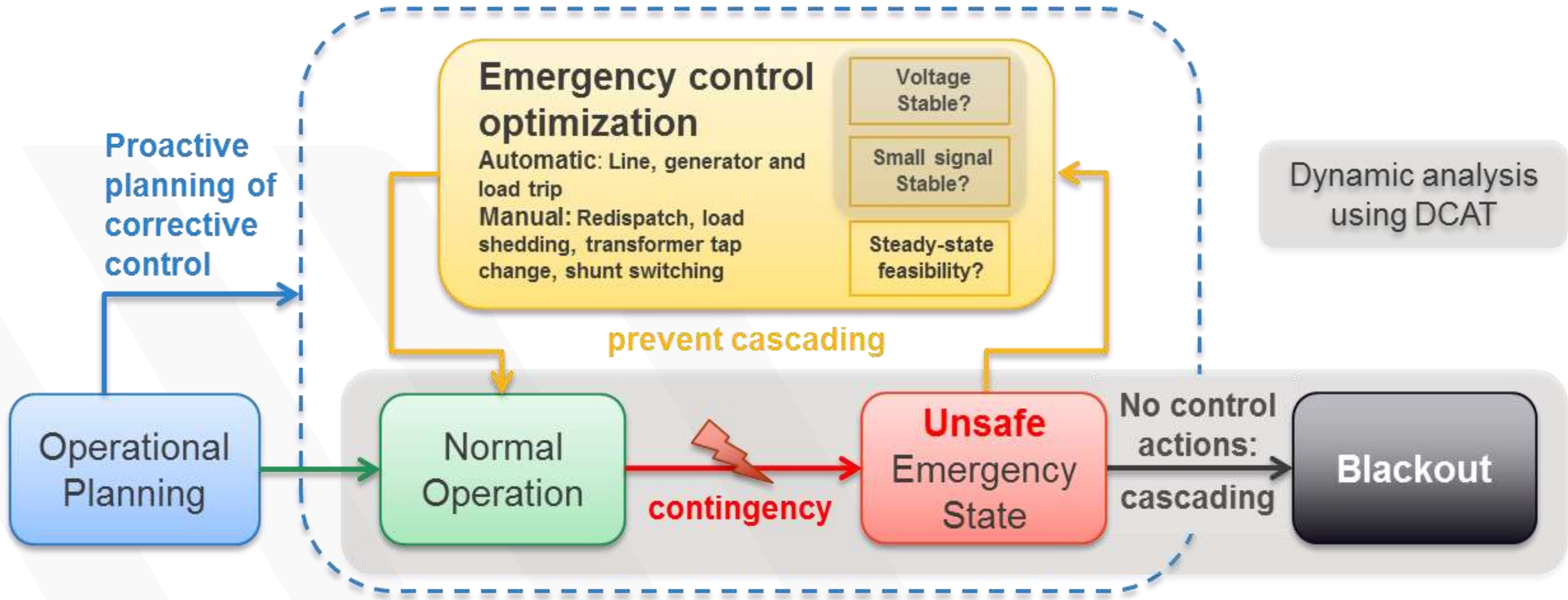
Pacific Northwest NATIONAL LABORATORY
OAK RIDGE National Laboratory
NRECA America's Electric Cooperatives
UF UNIVERSITY of FLORIDA
SOUTHERN CALIFORNIA EDISON An EDISON INTERNATIONAL® Company

Emergency Monitoring and Control Through New Technologies and Analytics (GM0076)

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

- Severe *contingencies* and unplanned *events* place transmission systems in *emergency* states where the system is vulnerable to cascading outages and blackouts
- Operators need *timing-aware decision support* to prevent further system degradation
  - **Real-time** computation of **emergency actions**
  - Selection of preplanned **corrective controls**
- Overreaching Goal : **effective real-time emergency control.**



Challenges *(for real-time emergency control to prevent cascading)*

- *Existing* methods for power flow optimization, voltage and small-signal stability analysis are *prohibitive* for real-time corrective control
- *Alternatives* are needed:
  - Amenable to real-time implementation
  - Accounting for AC power flow, voltage, and small-signal stability
  - Robust to uncertainties

Expected Outcomes *(for real-time emergency control)*

- *Theoretical formulation* of real-time emergency control as an AC-OPF which minimizes impact on the system and *guarantees* system *recovery*
- Computationally *light representation of* AC power flow *feasibility domains* to substitute AC power flow constraints. Derivation of convex domains through
  - Sufficient analytic conditions on power flow solvability
  - Machine learning methods with provable statistical guarantees
- *Linear* current-voltage optimal *power flow formulation* with accurate AC power flow physics, approximate representation of objective
- *Software implementation* of feasibility and small-signal stability domains and emergency AC-OPF
- *Numerical* testing and *validation* using Dynamic Contingency Analysis Tool (DCAT)
  - Robust testing tool for cascading outage analysis
  - Incorporates both automatic and manual emergency control actions

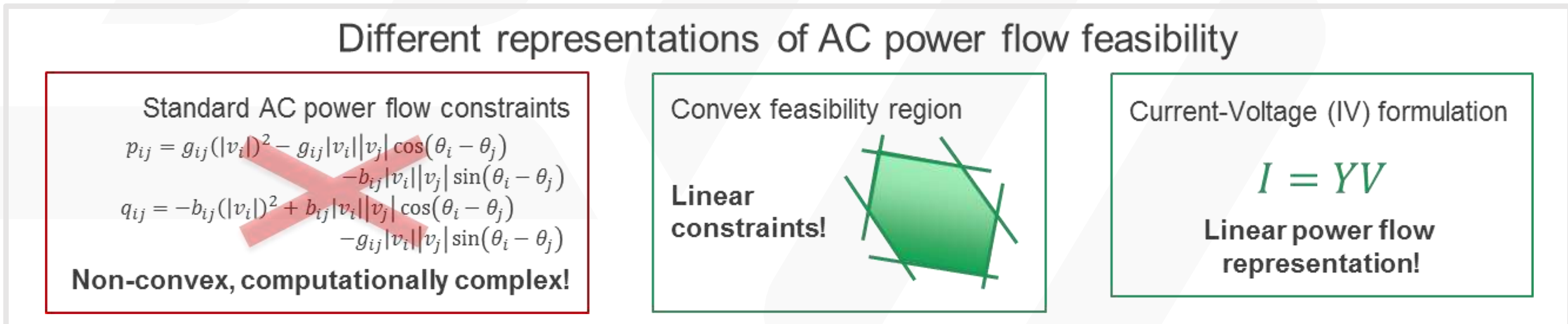
Publications

- *Two technical reports* submitted to DOE:
  - Road Map for Emergency Control of Electric Power Systems
  - Demonstration of Emergency Control Methods for Voltage Stability
- *6 peer-reviewed publications* prepared/submitted

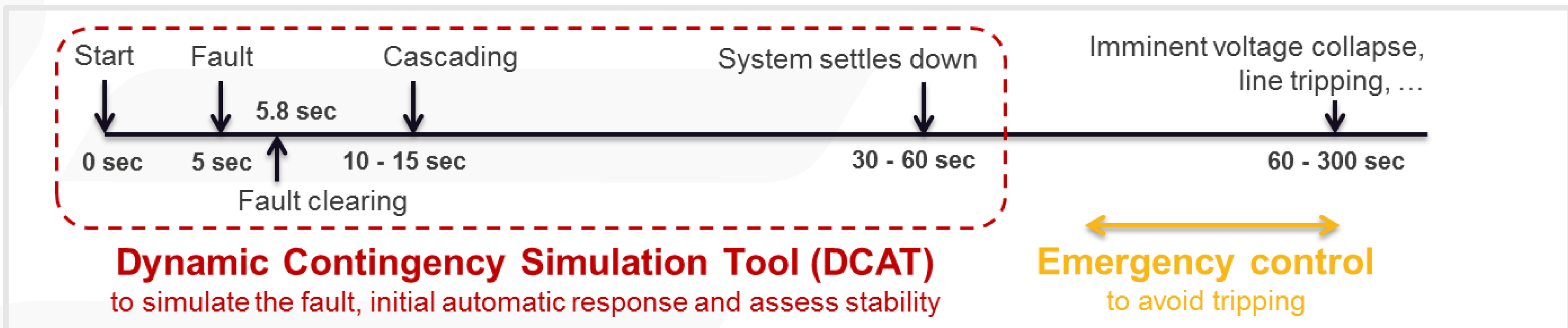
Progress to Date *(for real-time emergency control)*

- *Theoretical methods* development for computationally light AC OPF. We provide *formulation and implementation of*
  - Inner approximation of the AC power flow solvability region, using the analytic sufficient conditions [1-5]
    - contraction of the residual power flow operator [1 - 3]
    - monotonicity of the power flow operator in extended spaces [5]

    Provided set of convex constraints and improves state-of-the-art.
  - Current-voltage power flow representation [7] using
    - an inner approximation of the power flow constraints (too robust)
    - Taylor approximation (reasonable and efficient)
  - Sample-based feasibility domain approximation by convex polytope machines [5], sufficiently accurate in practice.
  - Severe Contingency Solver (SCS, [8]) to the problem shows good practical results.



- *Test-bed development* with DCAT
  - Power system model development (IEEE 118 bus, 300 bus and the Nordic case), to include dynamic components and protections relays.
  - DCAT integrated with manual and automated emergency controls to demonstrate prevention of voltage collapse and improving system security.
  - T-team voltage stability controls tested and implemented to ensure that the controls calculated with **steady-state methods are effective in avoiding voltage collapse**



[1] D. Lee, H. D. Nguyen, K. Dvijotham, K. Turitsyn. *Convex Restriction of Power Flow Feasibility Set. IEEE Trans. on Control of Network Systems (in review)*
[2] K. Dvijotham, H. Nguyen, K. Turitsyn, *Solvability regions of affinely parameterized quadratic equations*, IEEE Cont. Sys. Letters (V.2, Iss. 1, 2018)
[3] H. Nguyen, K. Dvijotham, K. Turitsyn. Construction of Convex Inner Approximations of Optimal Power Flow Feasibility Sets. IEEE Trans Power Systems (in review)
[4] Y. Suhyoun, H. Nguyen, and K. Turitsyn. *Simple certificate of solvability of power flow equations for distribution systems*, IEEE PES GM, 2015
[5] Y. Maximov, M. Chertkov, *Tractable Convex Approximations of Power Flow Feasibility Sets using Embedding in Larger Spaces and Machine Learning* (in preparation)
[6] L. Roald, S. Misra, T. Krause and G. Andersson, *Corrective Control to Handle Forecast Uncertainty: A Chance Constrained Optimal Power Flow*, *IEEE Trans on Power Systems*, March 2017
[7] S. Misra, L. Roald, M. Vuffray, M. Chertkov. *Fast and Robust Determination of Power System Emergency Control Actions*, *IREP, 2017*
[8] C. Coffrin, R. Bent, B. Tasseff, K. Sundar, S. Backhaus. *Relaxations of AC Minimal Load-Shedding for Severe Contingency Analysis*. arxiv: 1710.07861
[9] A. Owen, Y. Maximov. M. Chertkov. *Importance sampling the union of rare events with an application to power systems analysis.* Arxiv: 1710.06965. (in review)

GMLC 85 - System Research Supporting Standards and Interoperability

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Determine the feasibility of Plug-in Electric Vehicles (PEVs) providing grid services at the electric utility distribution level without negatively impacting grid stability or the PEV customer experience. Quantify the potential and benefits of PEVs providing grid services based on real-world utility conditions.

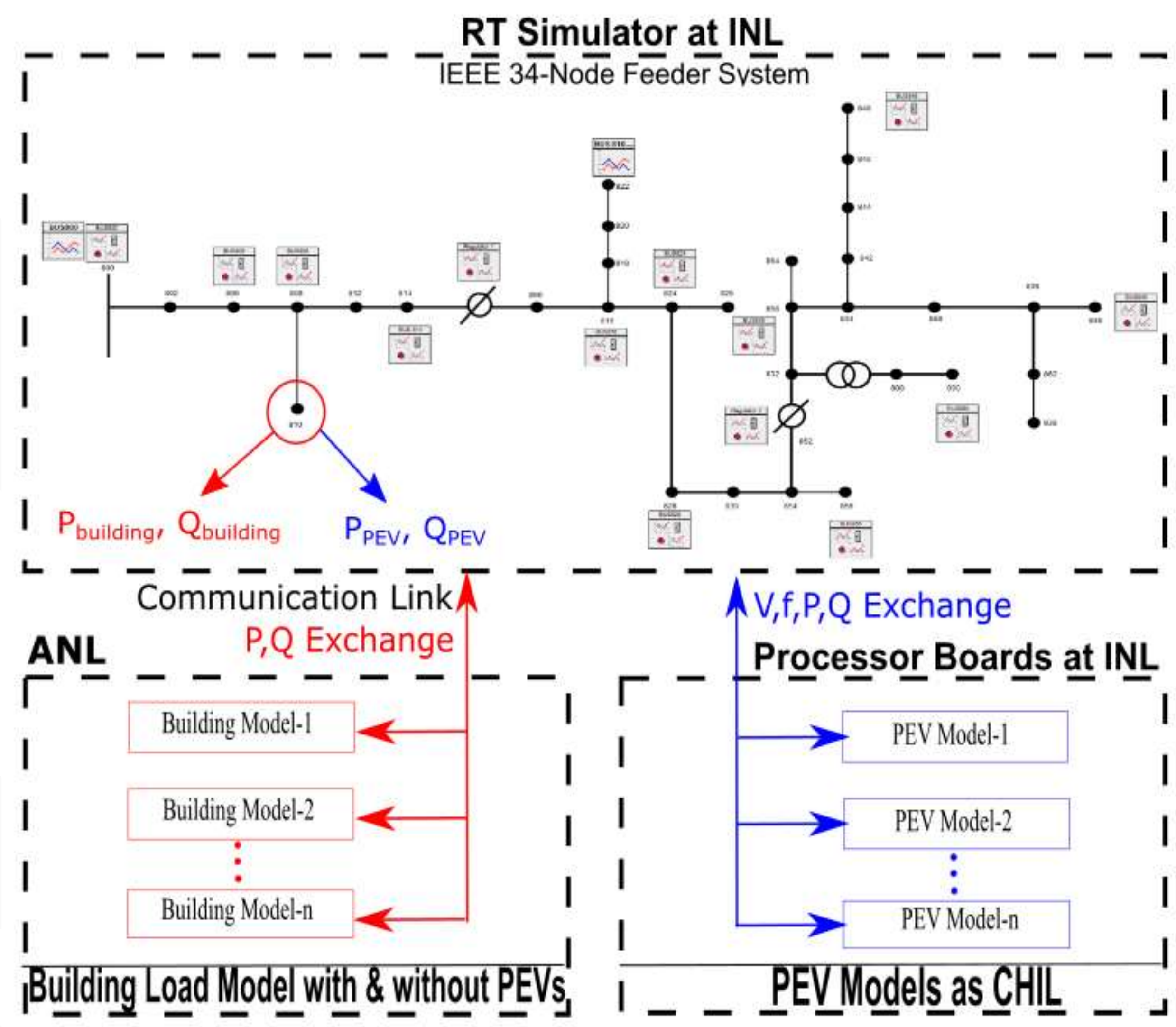
Expected Outcomes

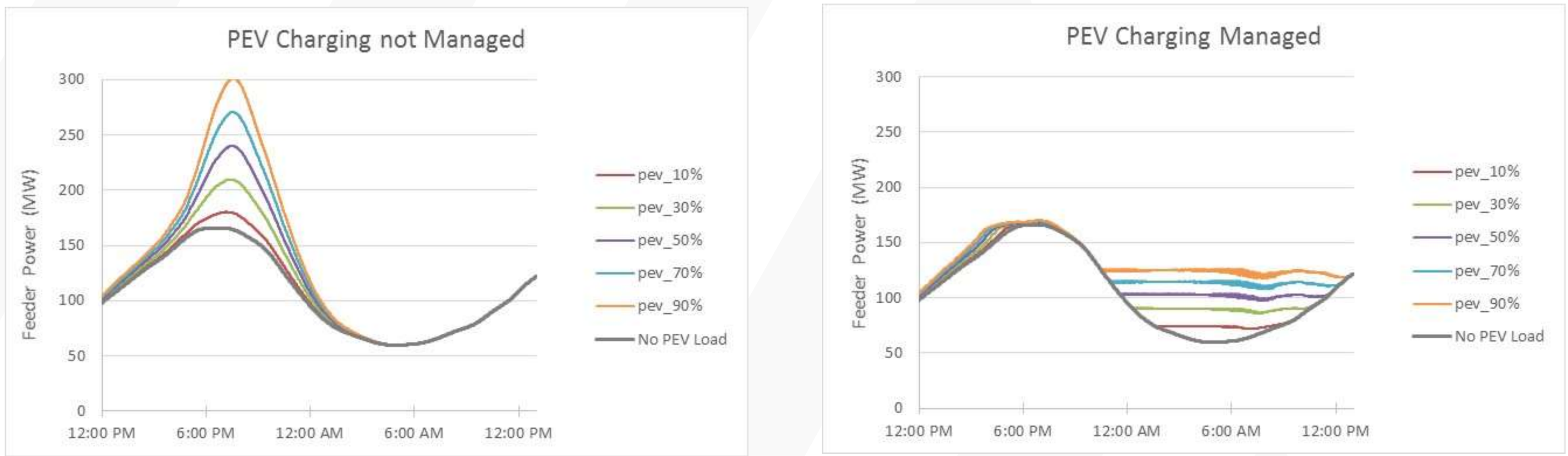
- Hardware-based verification and validation of provision of grid services by fleet of PEVs
- Control strategies to manage PEV charging at residences and commercial buildings
- Quantified benefits of controlling PEV charging
  - Cost savings of avoided distribution feeder upgrades
  - New generation capacity avoided

Progress to Date

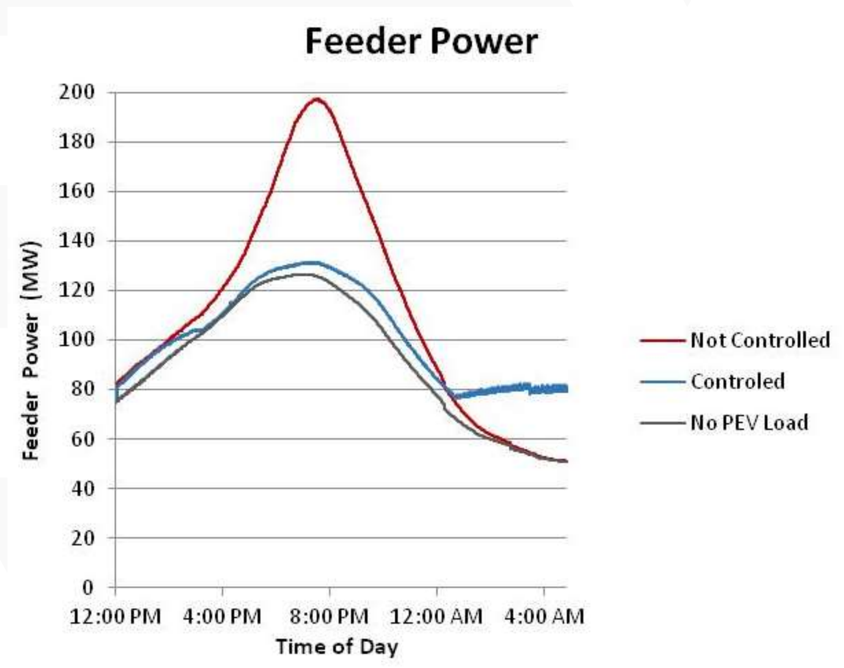
- Real-time assessment of PEVs and their impacts on distribution grid voltage and frequency in terms of stability
- Developed a methodology to control the charging of PEVs directly and quantify the provision of grid services
- Published 3 papers based on the findings of the project and 1 more is currently being submitted

Significant Milestones	Date
Complete a baseline demonstration of uncontrolled charging	Complete
Develop and verify a control strategy to manage the charging of PEVs at residences	Complete
Complete VGI study of at least 3 use cases, in which PEV charging is controlled to provide grid services	Complete
Develop and test building load data communication messages between ANL, INL, PNNL, and NREL	Complete
Demonstrate capability of the aggregator to communicate and integrate with the building control developed in GM0062	10/31/2018
Demonstrate capability of building control at ANL, PNNL, and NREL to respond to aggregator. Verify feedback from buildings can be integrated into the real-time simulation.	10/31/2018

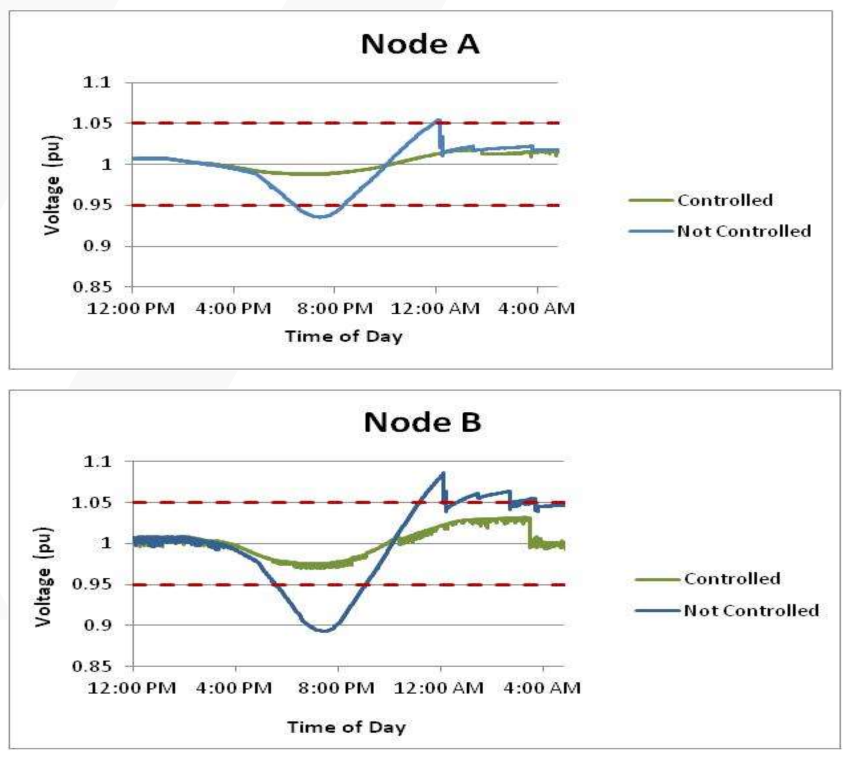




Feeder demand (MW) with and without an Aggregator for the following PEV penetrations (10%, 30%, 50%, 70%, 90%)



Controlled PEV Charging can Provide Capacity Deferral



Controlled PEV Charging can Provide Voltage Support

Partners

INL Idaho National Laboratory, Pacific Northwest National Laboratory, Berkeley Lab, NREL National Renewable Energy Laboratory, Argonne National Laboratory, SIEMENS Ingenuity for life

Unified Control of Connected Loads to Provide Grid Services Novel Energy Management and Improved Energy Efficiency

Teja Kuruganti, James Nutaro, Chris Winstead, Mahabir Bhandari, Brian Fricke – Oak Ridge National Laboratory
Srinivas Katipamula – Pacific Northwest National Laboratory
John Wallace - Emerson Commercial and Residential Solutions
Justin Hill, Pradeep Vitta – Southern Company

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

Develop a retrofit system for coordinating the operation of multiple loads to - reduce peak demand, reduce energy consumption, and providing transactive energy services to the electric grid.

Expected Outcomes

- Whole-building, retrofit, supervisory load control for improving energy efficiency and reducing peak demand by coordinating various building loads – HVAC & R
- Grid-responsive load control technology that can be deployed at large-scale to provide novel grid services
- Platform-driven technology for seamless self-aggregation of building-level loads for providing grid services
- Partnership with a building equipment manufacturer and an electric utility to demonstrate algorithms and techniques developed on an open-source control platform in real building sites

Significant Milestones	Date
Complete development of version 2 of VOLTTRON-based single board controller for HVACs in small/medium commercial buildings that performs peak load reduction and demonstrate grid-responsive load-shape generation using Priority-based Control (PBC) formulation	12/31/17
Complete development of VOLTTRON-based retrofit platform to aggregate HVAC and Refrigeration loads in small footprint supermarkets to provide load shaping and peak load reduction	3/31/18
Deliver draft report detailing survey of control formulations for wide-area decentralized control of loosely-coupled loads	6/30/18

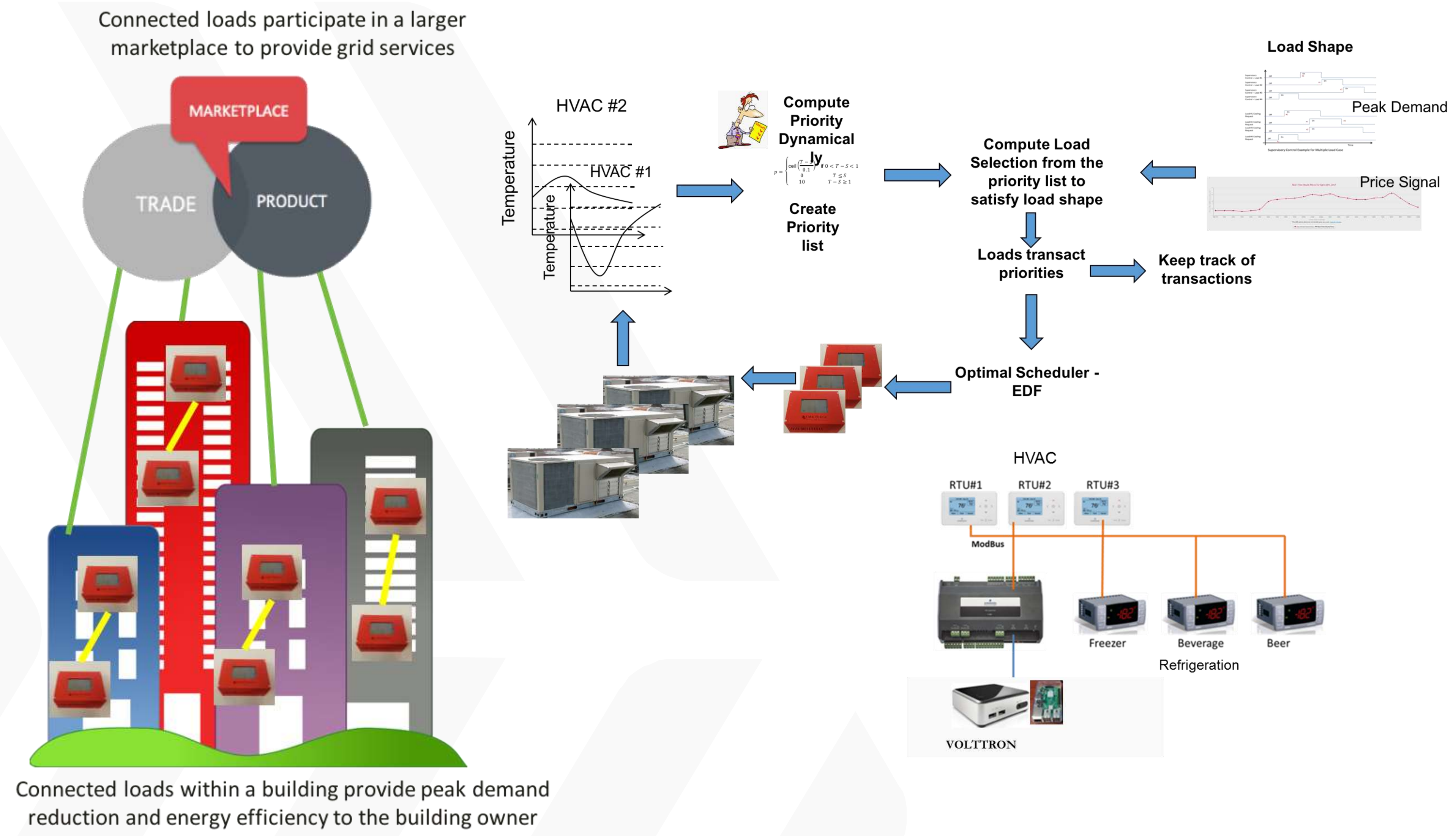


Figure 1: Transactive services enabled by connected loads

Progress to Date

- Priority Based Control deployed to VOLTTRON Thermostat in test location
- Control Tested across multiple summer months
- Proven Peak Load Reduction via coordinating multiple electrical loads
- Building supervisor satisfaction with deployed system and interface
- Control integration with Ecobee Smart Thermostat
- Survey Report of Control Frameworks for load shaping created including: Game Theoretic Control, Model-Free Control, Model Predictive Control, and Minimum Energy Control

VOLTTRON™ Controller for Economic Dispatch: Maximize Return-on-Investment for Building Integrated Fuel Cell CCHP Systems

GRID
MODERNIZATION INITIATIVE
U.S. Department of Energy

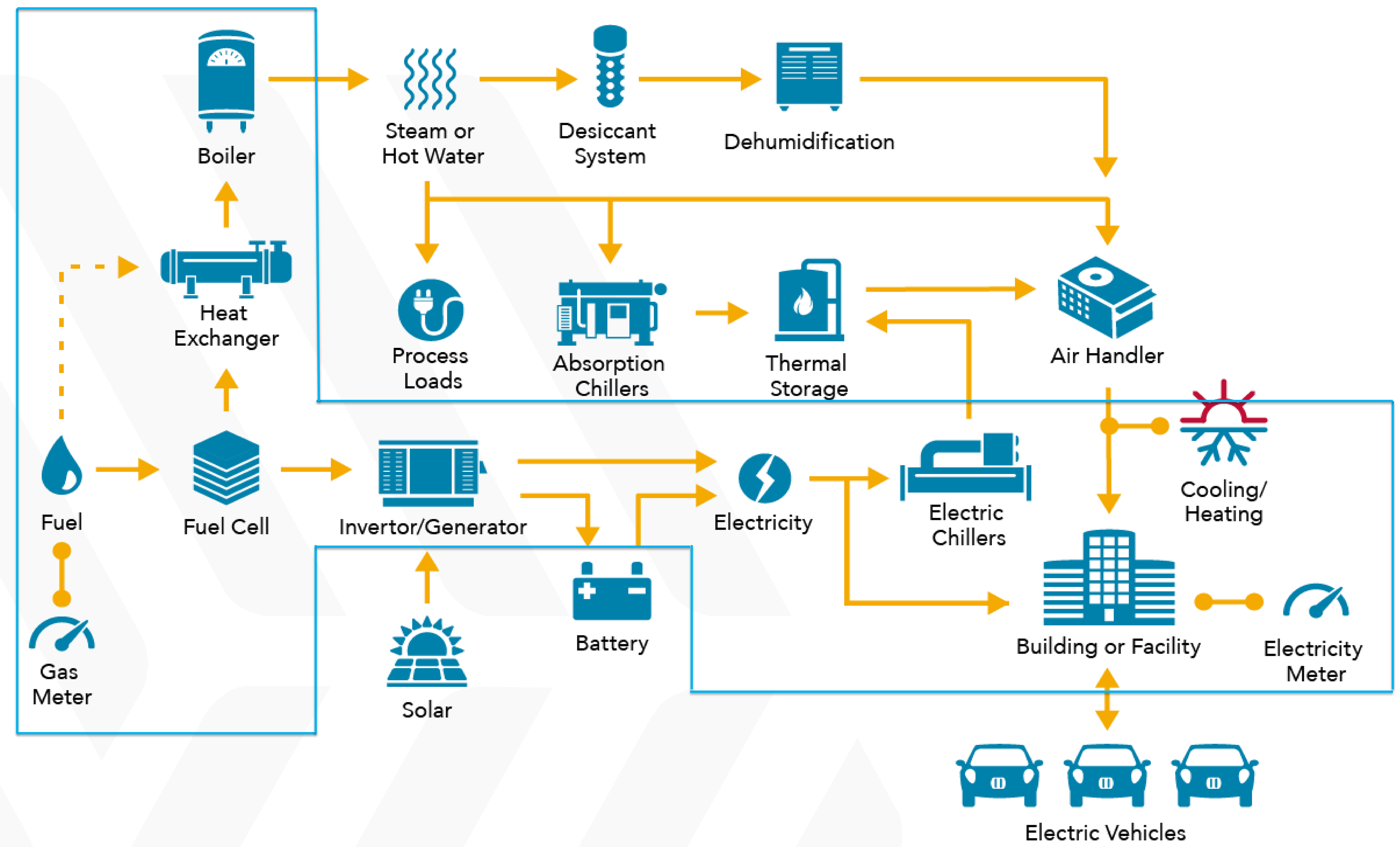
Project Description

This project develops a multi-purpose, open-source economic dispatch application to ensure automated optimization of combined cooling, heating and power (CCHP) systems.

Expected Outcomes

- Maximum return-on-investment of CCHP
- VOLTTRON™-compatible real-time control algorithms, packaged as a fully functional toolkit
  - Supervisory control and generalized automated economic dispatch
  - Short-term weather and load forecasting
  - Management of short-term imbalance between local generation and demand
  - Performance monitoring and fault detection
  - Automated continuous commissioning
- Contributions to DOE Building Technologies Office, Grid Modernization Laboratory Consortium and Grid Modernization Initiative goals
- **Ultimately, increased electric grid reliability and hosting capacity of renewable generation assets**

Significant Milestones	Date
Testing of algorithms with offline data - complete	6/30/17
Integration of all algorithms with VOLTTRON™ - complete	3/31/18
Field validation and documentation of results - on track	3/31/19



Integrated Energy System: *System, as outlined in blue, is the original scope; however, the framework will be general and support the rest of the CCHP system.*

Progress to Date

Completed:

- Component models, and conversion to Python
  - Draft final report and 3 journal papers accepted; 3 additional papers in preparation
- Optimization framework - conversion to Python, use case tests, and benchmarking
- EnergyPlus hospital prototype with CCHP system, and integration with VOLTTRON™
- Algorithm integration with VOLTTRON™
- Automated Fault Detection and Diagnostics and conditioned-monitoring algorithms
- In progress: Adaptive update of component models and field validation of economic dispatch software with real equipment

VOLTTRON
Common Message Protocols

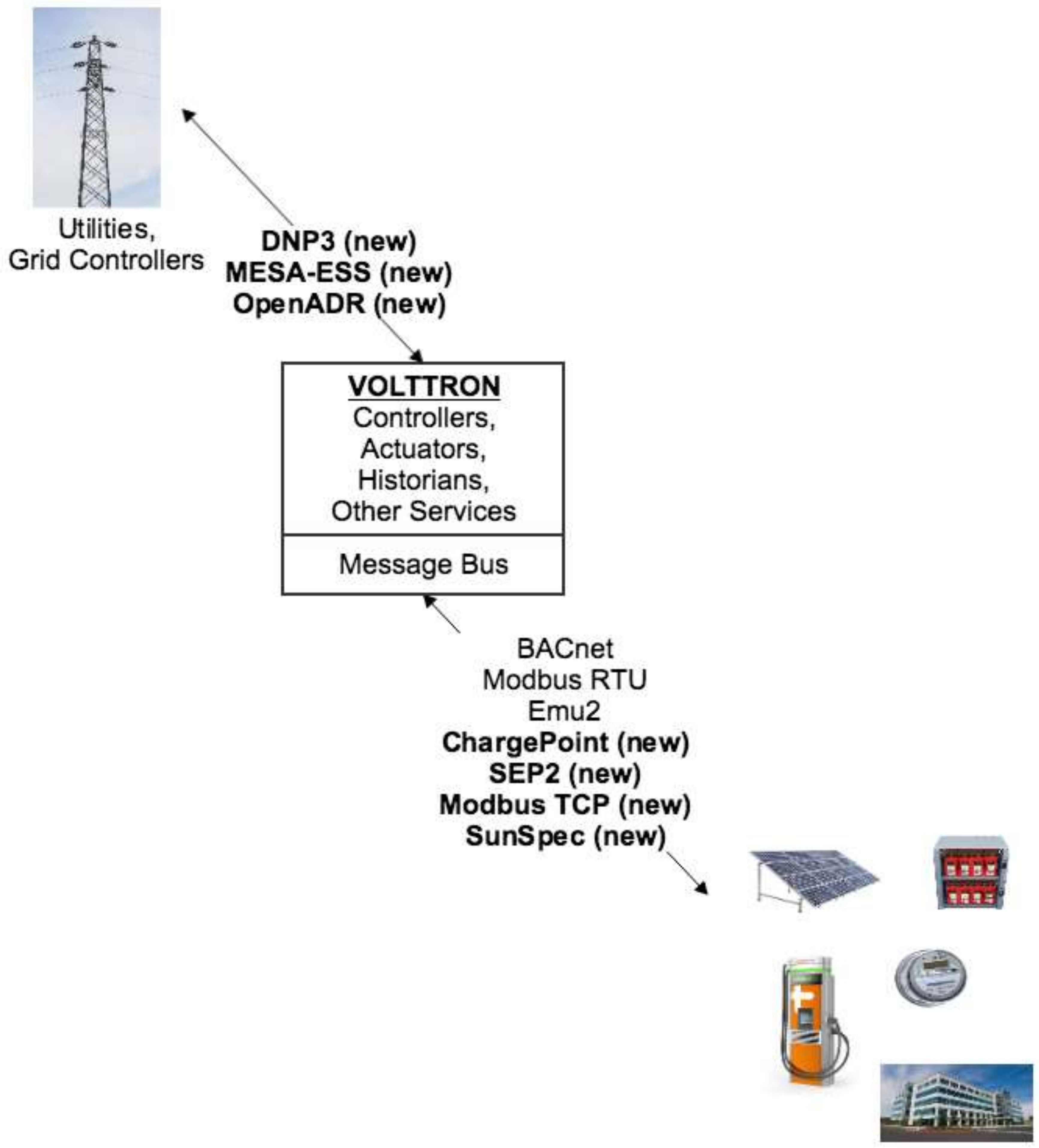
GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

This project adds DER management features to VOLTTRON, implementing agent support for commonly-used DER protocols including Modbus TCP, SEP2, DNP3, MESA-ESS, SunSpec, and ChargePoint. Support has also been added for a RabbitMQ message broker.

Expected Outcomes

- **Integration of DER and smart meters**: Support has been added for: device monitoring, demand response/load control, EV charging optimization, and DER energy optimization.
- **Open source interfaces to key protocols**: VOLTTRON's existing Modbus support is extended with support for TCP as well as serial communications. A SEP2 (IEEE 2030.5) agent supports DRLC use cases. A ChargePoint EVSE driver enables EV smart charging across the largest vehicle charging network in the US. A SunSpec driver will enable DER management of PV arrays and other SunSpec-compliant devices.
- **Open source SCADA controls and transactive power optimization**: DNP3 and MESA-ESS agents enable grid control of connected DERs. An OpenADR agent implements demand response.
- **Robust, Scalable Platform:** The ability to run VOLTTRON with RabbitMQ, a widely-used open-source message broker, helps ensure that the platform will continue to evolve and scale.



Significant Milestones	Date
Year 1	
ChargePoint EVSE Device Driver	Dec 2016 (DONE)
SEP2 DRLC Agent with SunSpec Data Model	Jun 2017 (DONE)
Year 2	
Modbus TCP Device Driver	Dec 2017 (DONE)
DNP3 and MESA-ESS Agents	Apr 2018 (DONE)
3rd Party Message Broker API	Aug 2018
SunSpec Device Driver	Mar 2019

Community Control of Distributed Resources for Wide Area Reserve Provision

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Team: LBNL (lead), NREL, Sandia, Smarter Grid Solutions, Riverside Public Utilities

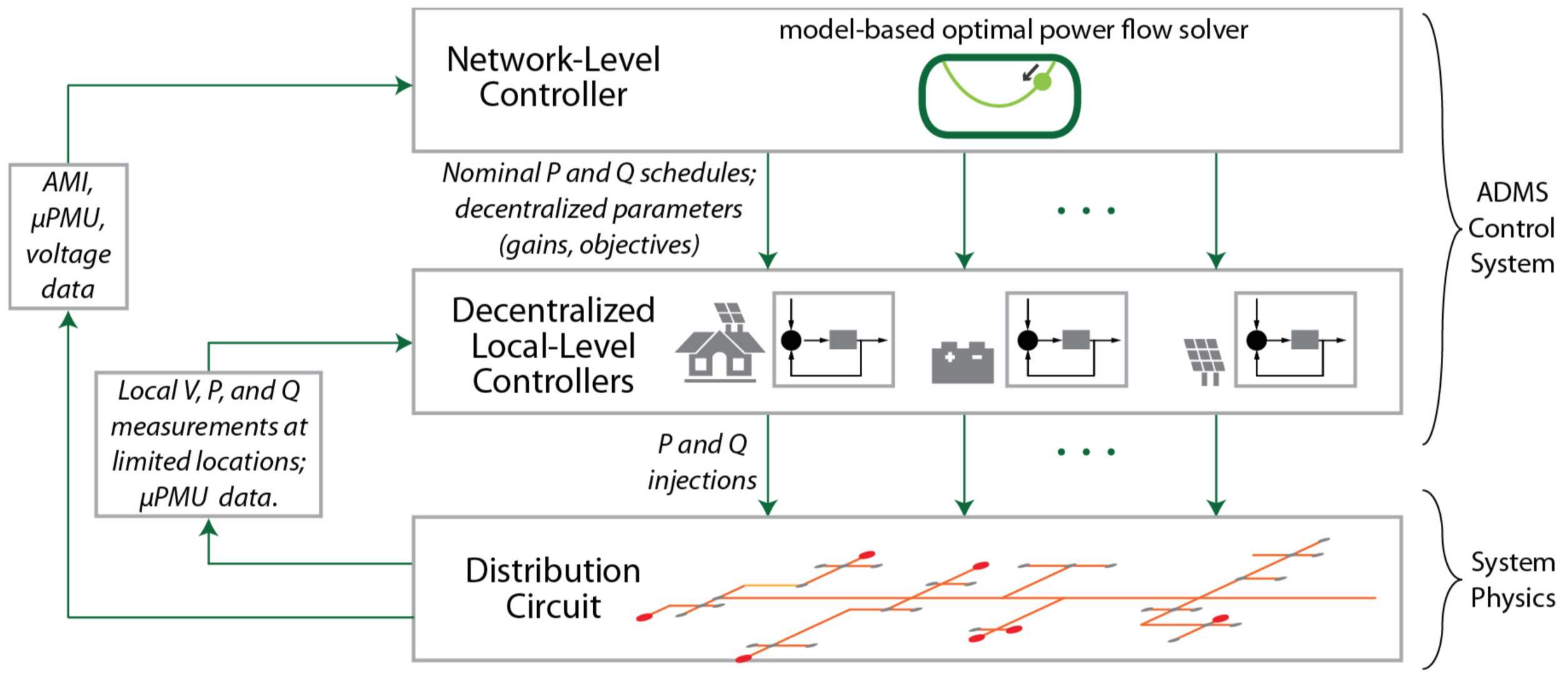
Project Description:

Our goal is to develop and demonstrate an advanced distribution management system (ADMS) that allows DERs to improve distribution system operations and simultaneously contribute to transmission-level services. In short, we envision **(1) elevating load buses to the level of generator buses** with respect to the degree of control they present to system operators and **(2) simultaneously optimizing distribution system operation** (i.e. ensuring voltage regulation).

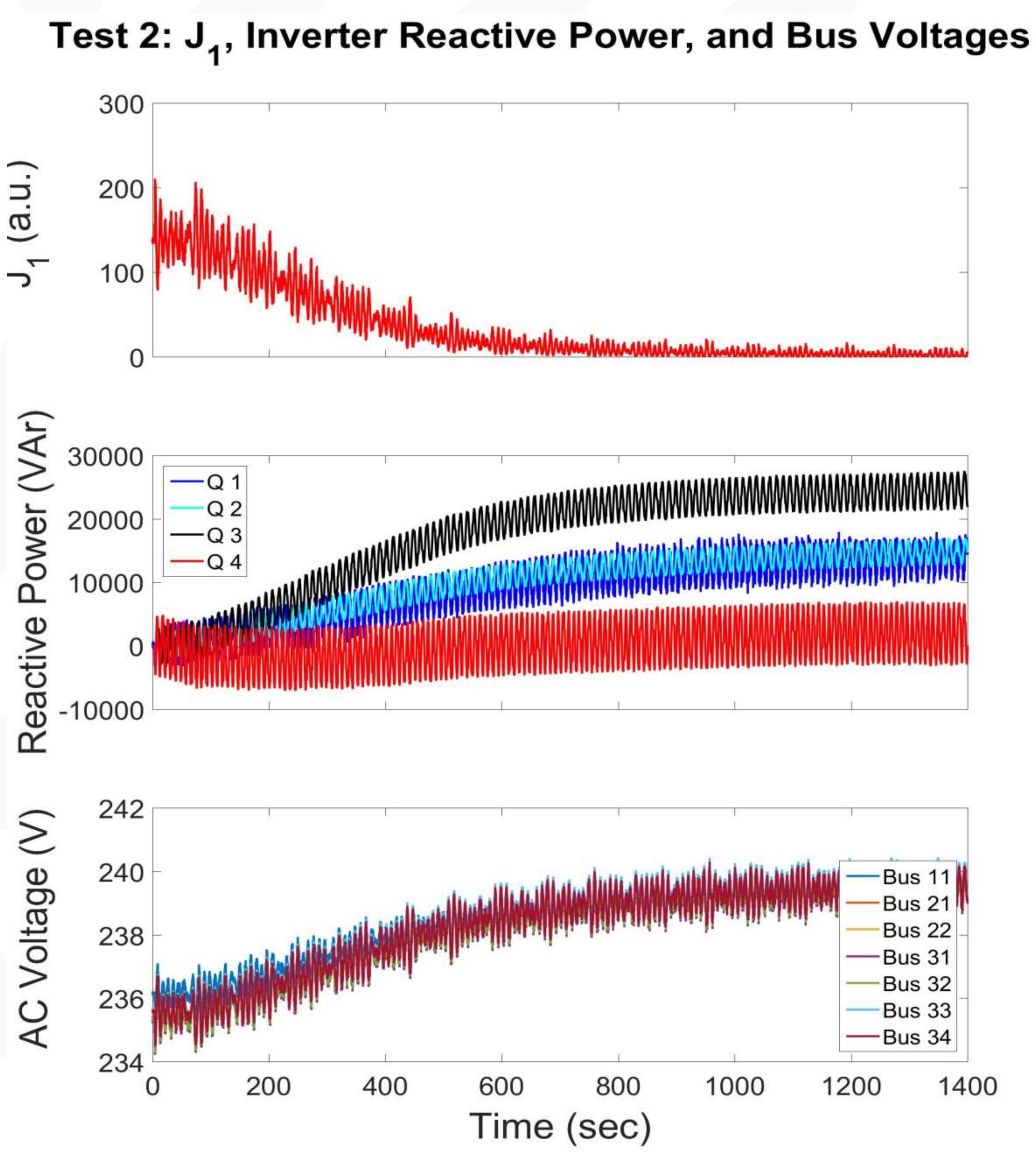
Expected Outcomes:

- New real-time decentralized optimization tools for controlling distribution systems with minimum utility investment (model free control with limited communications)
- Hardware-in-the-loop tests of PV and battery systems for network management
- Implementation on industry partner's existing DER management platform

Significant Milestones	Date
Initial implementation of decentralized control for voltage support complete and simulated.	April '17
Optimization and forecasting algorithms implemented in simulation	April '18
Hardware in the loop (HIL) tests designed, small simulations demonstrated	Aug. '18
Integration of control algorithms and data streams into SGS platform for HIL demonstration.	April '19
Transmission- and distribution-level benefits quantified	April '19



Hierarchical control solution schematic



Experimental Results:
Four DER inject reactive power using Extremum Seeking algorithm to move the feeder voltages up toward 240V
(real inverters)

Progress to Date:

- Extremum seeking decentralized control successfully tested on PV inverters in Sandia Distributed Energy Test Lab (DETL)
- Extremum seeking decentralized control algorithm successfully integrated and demonstrated in control hardware in the loop setup
- Publications: IEEE Trans. Power Systems (2), IEEE Journal of Photovoltaics (accepted), HICSS (accepted)

Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller) (GMLC0252)

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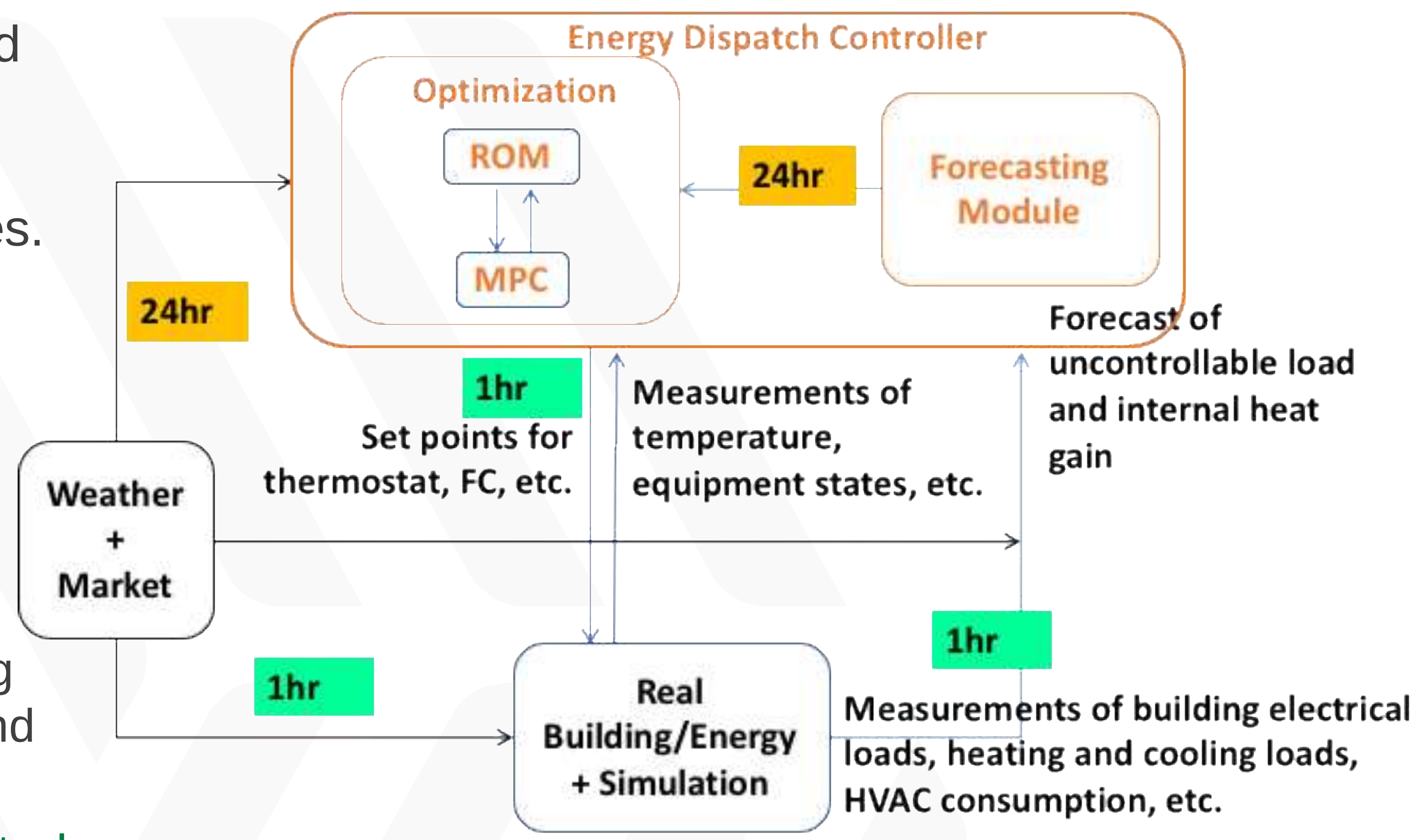
U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY
FUEL CELL TECHNOLOGIES OFFICE

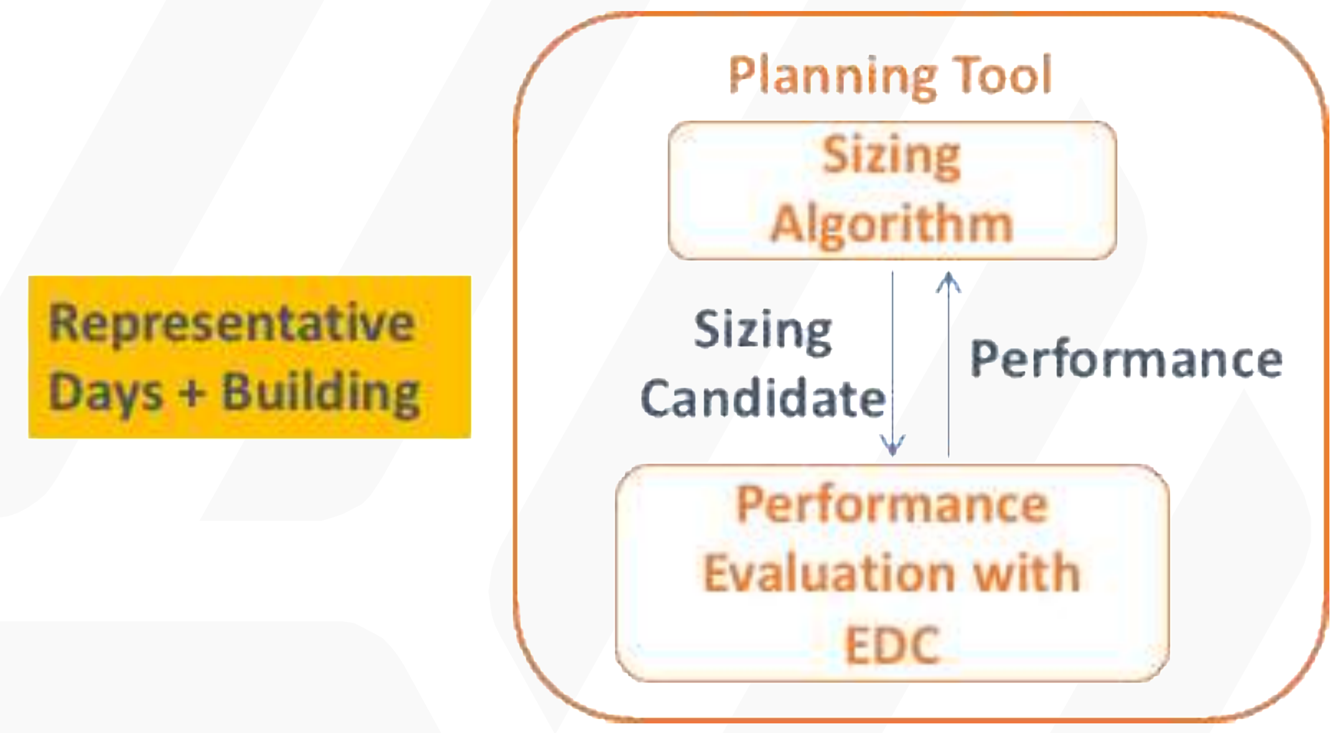
Project Description

- Create an open-source novel energy dispatch controller (EDC) to provide optimal dispatch for fuel cells and other combined heat and power (CHP) generators, controllable building elements and components, thermal and electrical storage, renewables, and transactive communication for participation in ancillary grid services. Integrate this optimal dispatch knowledge into a planning tool for building component sizing.
- Energy Dispatch Controller & Planning Tool



Expected Outcomes

- Fills need for better energy management of integrated buildings
  - Allows the wealth of information provided by distributed sensing technology throughout a building to be used for cost savings and grid support. Not currently well-used.
- Increases benefit of distributed energy resources (DER) in integrated buildings
  - Reduces energy bills and emissions
  - Improves on-site energy reliability and security
  - Maximizes benefits of CHP, heat capture, storage, and other renewable generation
- Expands grid supportive features of smart buildings and distributed energy resources for grid modernization.
  - Increases grid reliability and security and supports local deployment of variable DER using a flexible, dispatchable energy resource
- Supports fuel cell market development
  - Quantifies economic benefit of integrated CHP
  - Informs the industry of favorable transient characteristics for the dynamic performance of fuel cells



Significant Milestones	Date
Feedback on graphical user interface (GUI) functionality	6/30/17
Verify source code runs on two operating systems (OS)	6/30/17
Select VOLTTRON agents to implement for communications backbone	12/20/2017
Provide initial co-simulation results and review of dispatch controller	3/30/2018
Demonstrate run time of 5 min or less dispatch optimization in at least 2 test cases	6/29/2018
Select search algorithms for optimal planning tool	6/29/2018
Show successful communication with at least 2 VOLTTRON agents	9/28/2018
Demonstrate energy planning tool with at least 3 test scenarios	9/30/2019

Progress to Date

- Energy Dispatch Controller
  - Initial optimization formulation complete
  - Testing using closed-loop simulation with temperature feedback for ongoing evaluation
  - Improving building reduced-order model (ROM)
  - Development of VOLTTRON agents for communication
  - Preparing for hardware-in-the-loop testing (FY19)
- Energy Planning Tool
  - Initial search algorithms implemented
- Lin, Y., McLarty, D., Pratt, A., Ball, B., Henze, G., Saur, G. Optimal dispatch controller for fuel cell integrated building, 5th International High Performance Buildings Conference at Purdue, West Lafayette, IN, USA, July 09-12, 2018.

Operational and Strategic Implementation of Dynamic Line Rating for Optimized Wind Energy Generation Integration

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Affordable and effective implementation of real-time weather and forecast based dynamic line rating of overhead transmission lines by mitigating transmission congestion and optimizing the use of electricity infrastructure for the integration of wind energy to enhance the nation's energy portfolio.

The Challenge:
Provide science based methodologies and solutions that are readily adopted and usable by a regulated industry

Requirements:
Provide industry with a low cost, robust solution set, and enabling human operators to make informed decisions and take appropriate actions without being overwhelmed with data.

Expected Outcomes

- ✓ Research will extend IEEE and CIGRE DLR standards to an industry approved True Dynamic Line Rating (TDLR) calculation algorithm to provide utilities forecast capabilities and improved situational awareness for optimization and risk reduction and improved infrastructure security.
- ✓ Transmission Route Engineering Analyzer and Designer (TREAD) is an industry partner-informed application to utilize DLR data to choose the most economical transmission line conductor and route for new construction and line upgrades for increased wind generation
- ✓ Inform advanced control room implementation using human performance and cognitive psychology
- ✓ Develop methodology to secure real time data streams from distributed sources

Significant Milestones	Date
Performed real-time assessment of DLR pilot project (CRADA) with AltaLink	FY16
Installed Beta version of DLR Methodology (GLASS) at Idaho Power	FY17
Hosted First International DLR Workshop with more than 75 attendees at INL	FY18
R&D 100 Finalist for GLASS	FY18

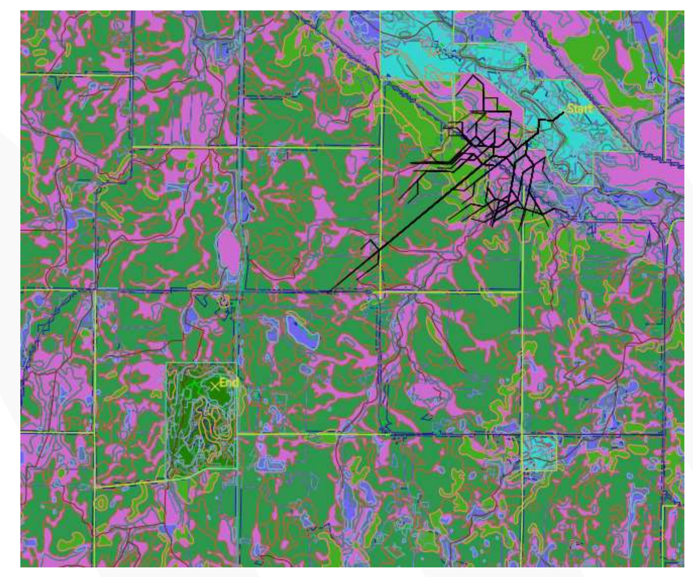

Figure 1. Visualization of Computerized routing

$$I_{TDLR}(i) = \sqrt{\frac{C_p\rho\,(Tc_{max} - Tc_{margin} - Tc(t_o))}{R(Tc_{max})t_r} + f(Iss(i)^2)}$$

Figure 2. True Dynamic Line Rating Equation

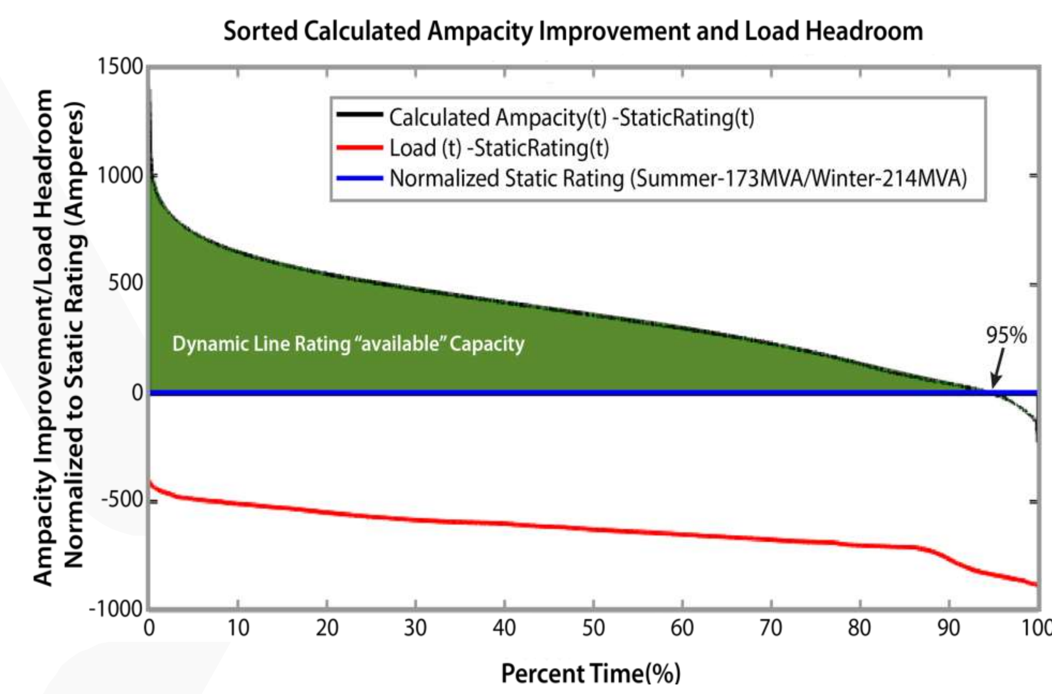

Figure 3. Altalink Case Study Results showing DLR enhancements over static ratings

DLR Accomplishments to Date

Standards – Significant participation in IEEE and CIGRE standard working groups and task forces. PI is one of two U.S. Delegates on CIGRE Working Group B2.59: Forecasting Variable Line Ratings. Reports published in 2018.

Publications – 10+ peer reviewed journals, **25+** conference proceedings, **50+** invited presentations, Best Conference Paper on Markets, Economics, and Planning (IEEE PES GM), IEEE Transactions on Power Delivery (2018).

Workshop – INL | DOE | UVIG hosted the Dynamic Line Rating Workshop November 7-9, 2017 in Idaho Falls, ID.

Integration with NOAA – Using HRRR data to improve GLASS forecasting.

Commercialization – Copyrights asserted, DOE Energy I-Corps commercialization strategy with industry partners.

Interactions w/ Industry & Academia – 16 Non-Disclosure Agreements, **1** SPP agreement executed, **2** CRADA projects executed, **1** CRADA project underway.

Dynamic Building Load Control to Facilitate High Penetration of Solar PV Generation

Teja Kuruganti, James Nutaro, Yaosuo Xue, Jin Dong, Mohammad Olama, Christopher Winstead, Arjun Shankar - Oak Ridge National Laboratory (ORNL)
Justin Hill, Pradeep Vitta – Southern Company
Seddik Djouadi, Bhagyashri Telsang– University of Tennessee, Knoxville
Godfried Augenbroe – Georgia Tech

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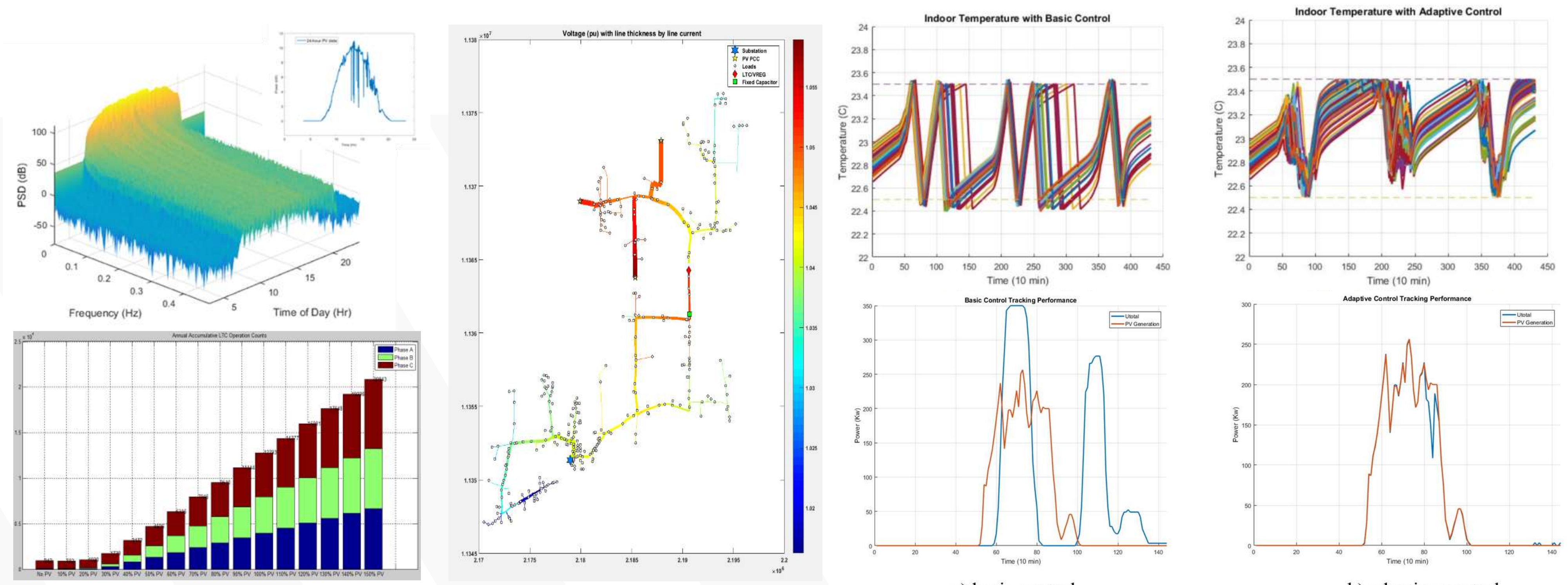
Project Description

Enable responsive building loads that can be controlled temporally and spatially to minimize the difference between demand and PV production to minimize voltage variation and reduce two-way power flow

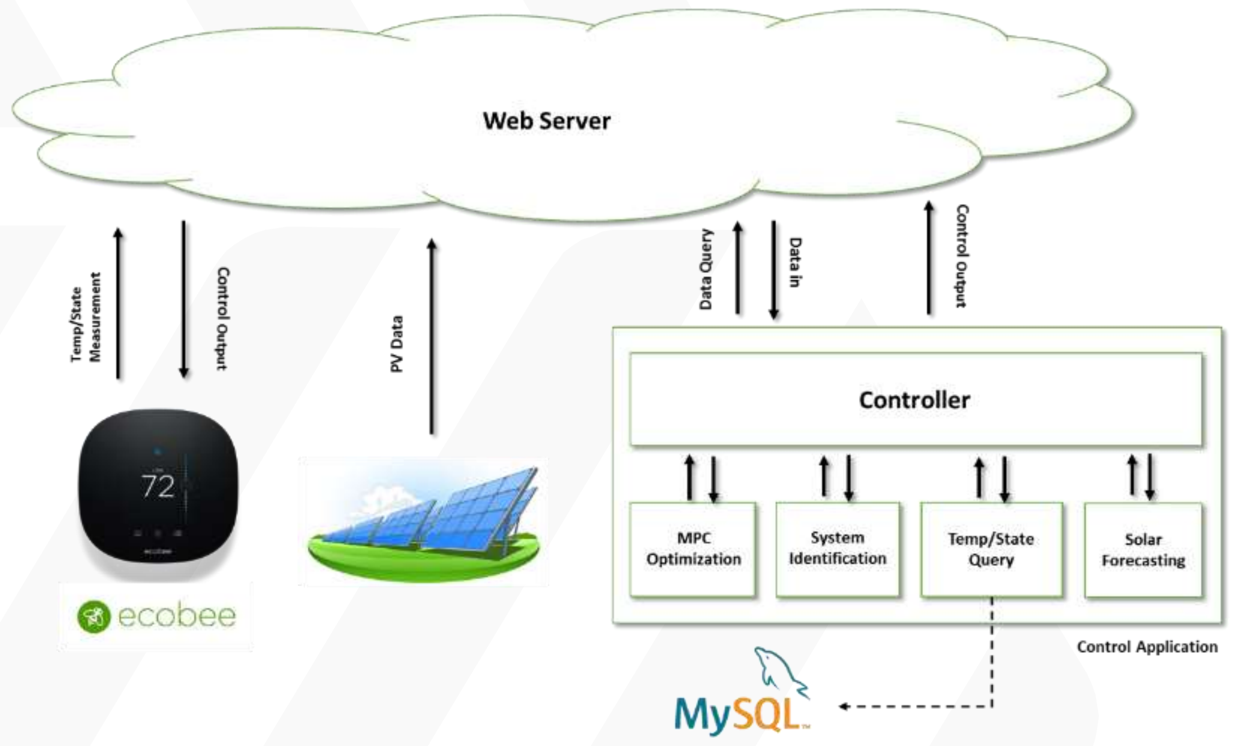
Expected Outcomes

- Low-cost, low-touch control retrofits to distributed PV and building loads that enable load-shaping response in order to facilitate high-levels of renewable penetration
- Open-source software and hardware specification of the control platform to enable load integration and deployment

Significant Milestones	Date
Developed deployable software using open source software packages that enables model-predictive control of building loads to demonstrate its performance during the control design phase	10/31/17
Developed dynamic models of distribution circuits and transformers, building systems, and PV system for the accurate open-source integration simulation framework for end-to-end control design	1/31/18
Simulated the effect of varying levels of PV (10-100% of peak load) in the Southern Company's feeder with and without coordinated load control	1/31/18



a) basic control
b) adaptive control



Progress to Date

- Novel method using spectral analysis of solar PV generation to determine optimal utilization of loads as distributed energy resources
- Detailed simulation-based analysis of solar PV integration at increasing penetration levels (up to 150%) using one-year worth of PV data to demonstrate the impact on the distribution circuits
- End-to-end open-source modeling and simulation package to enable PV responsive load control
- Open-source adaptive load control solution for coordinating multiple buildings' loads to enable high penetration of PV
- Thirteen articles published (best paper award at the PEDG'18). Two publications under preparation

A Tool-Suite for Increasing Performance and Reliability of Combined Transmission-Distribution under High Solar Penetration

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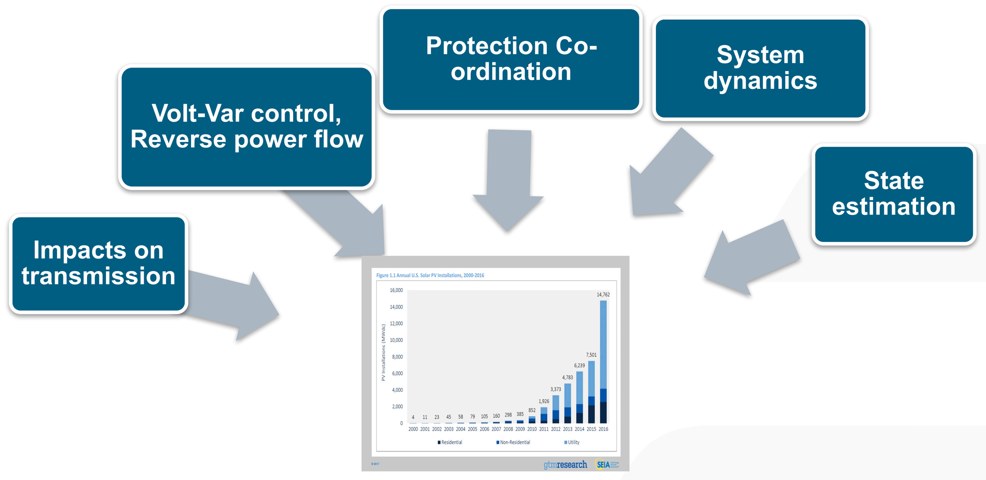
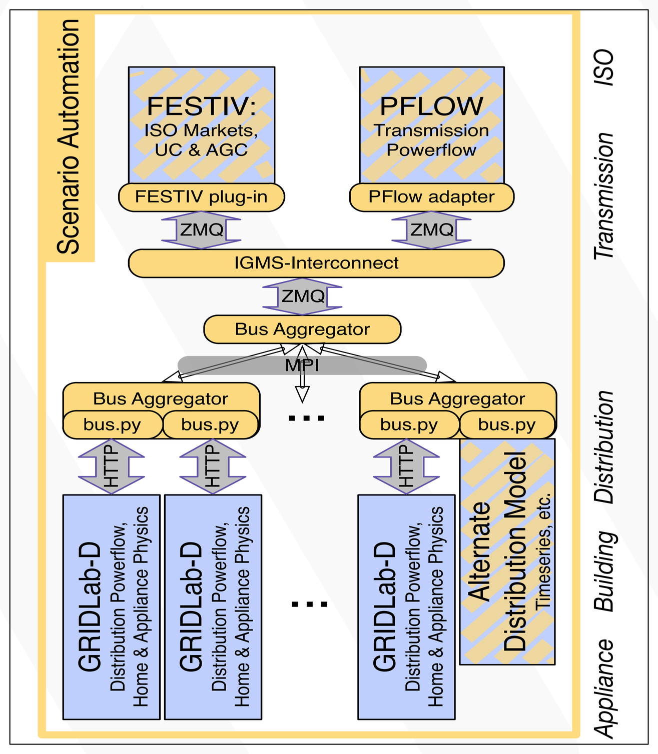
U.S. Department of Energy

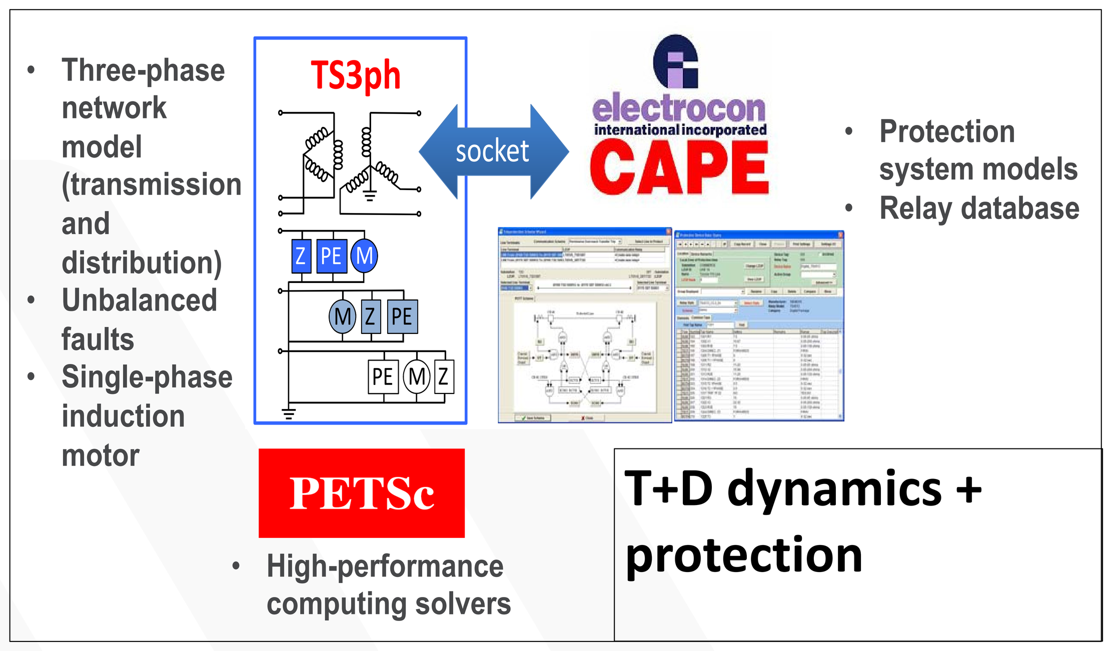
Project Description



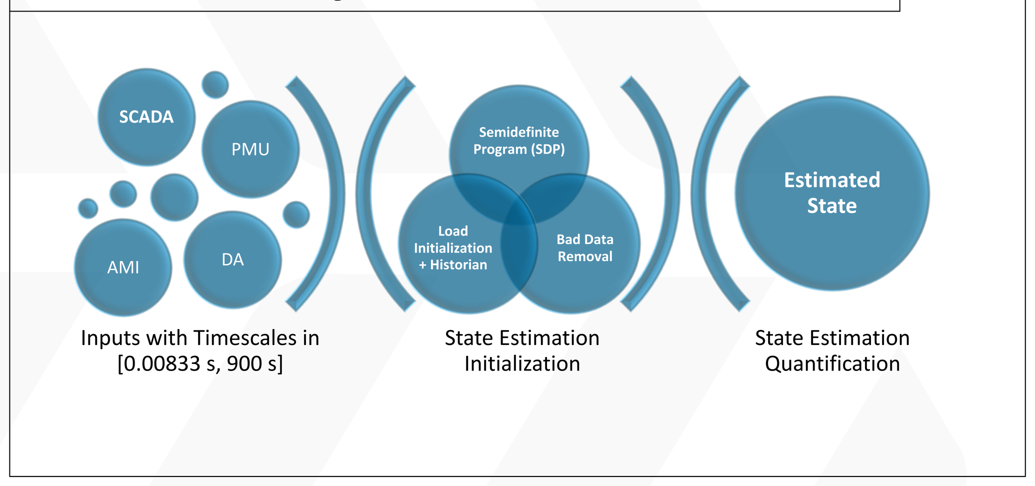
Develop a suite of software tools that impart a holistic understanding of the steady-state and transient behavior of transmission-distribution interaction under high PV penetration with real-time monitoring of the distribution system and integration of system protection

T+D steady-state analysis

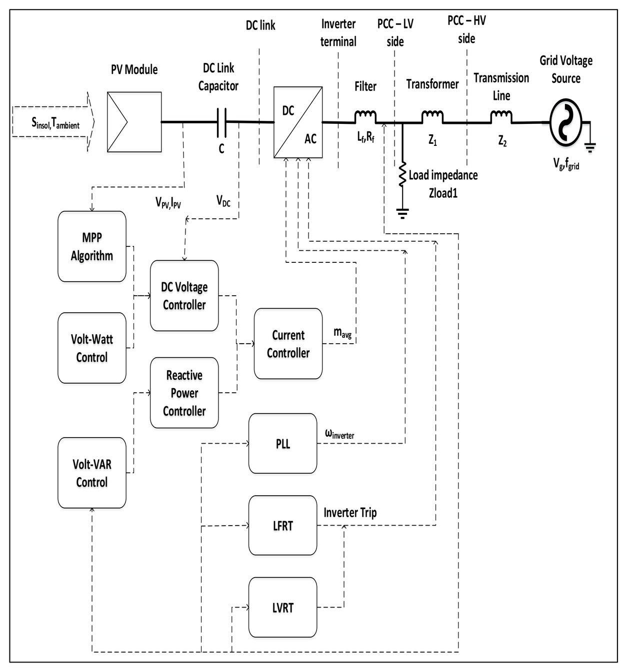




Distribution system state estimator



New Phasor model of DGPV



Expected Outcomes

Steady-state analysis Tool
- Combined transmission-distribution
- New models of subtransmission/distribution substation
- Quasi-static analysis (less than 5 second time-step)
- Tool publicly available at end of 2018

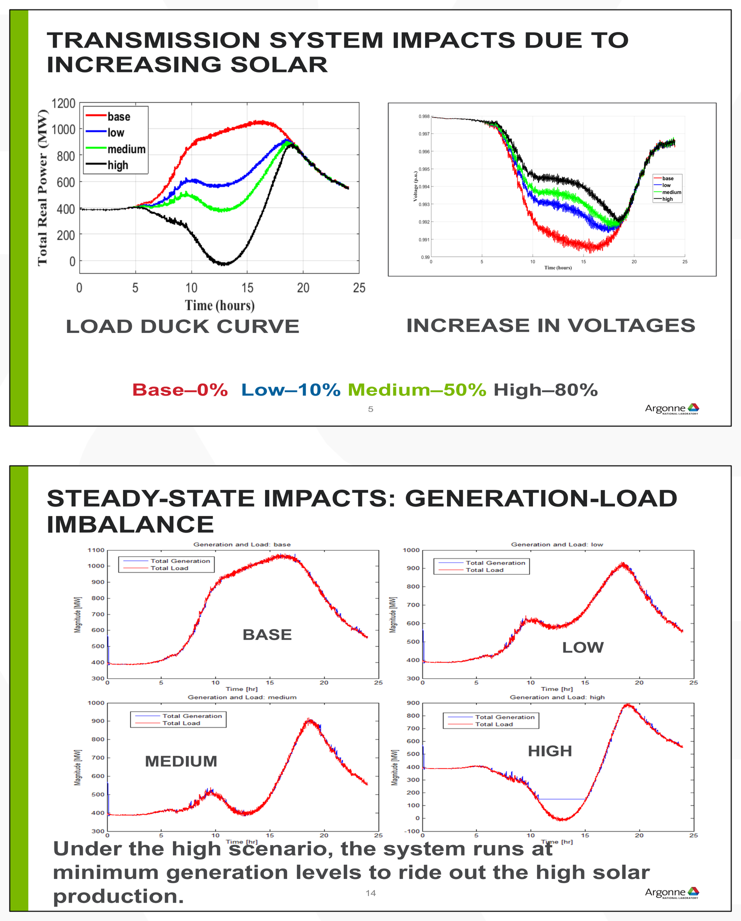
Dynamics and Protection Tool
- Combined transmission-distribution
- Integration with protection models
- New solar PV models using dynamic phasors

Distribution state estimation Tool
- Unbalanced distribution system state estimation
- Inclusion of AMI, PMU, and other sensor measurements
- Semi-definite programming based approach

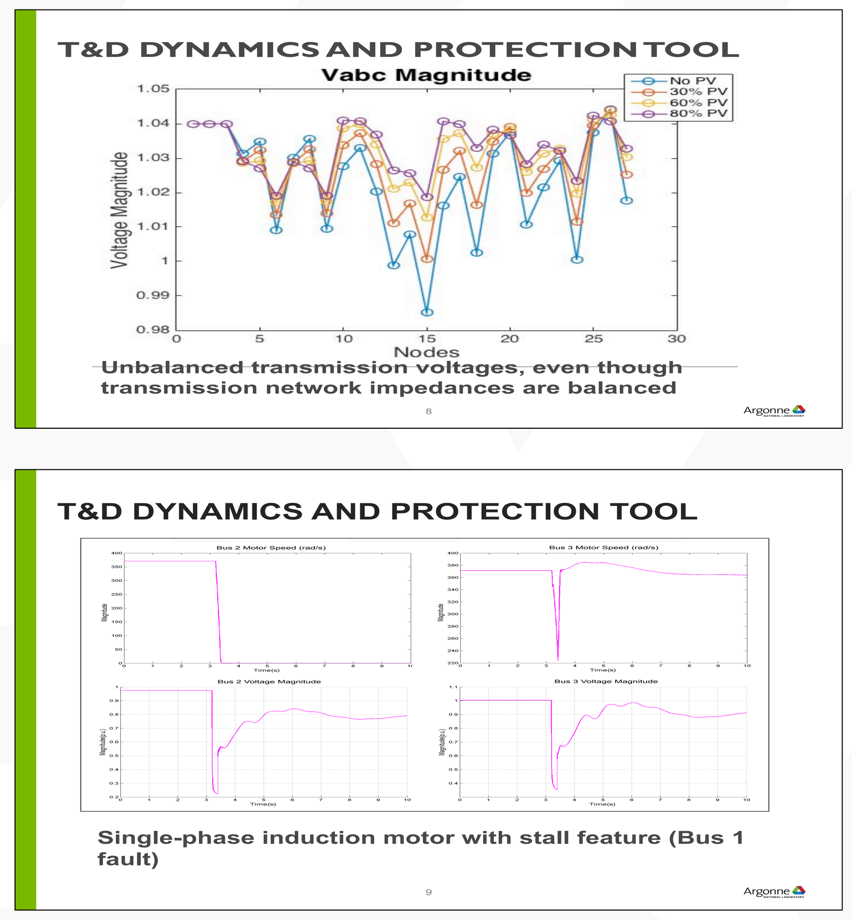
Significant Milestones	Date
Set up utility advisory group with three participating utilities (HECO, PG&E, and SPP)	Oct. 2016
A total of seven use-cases defining high solar integration challenges have been developed	Jan. 2017
Demonstrate functionality of the three developed tools	Apr. 2017
Utility data preparation and Windows-based combined stready-state T&D platform development	Apr. 2018
Dynamic phasor model of distributed solar PV system	Apr. 2018
Advanced development of T&D dynamics and distribution system state estimator	Apr. 2018
Use-case simulation and analysis on utility data	Apr. 2019

Progress to Date

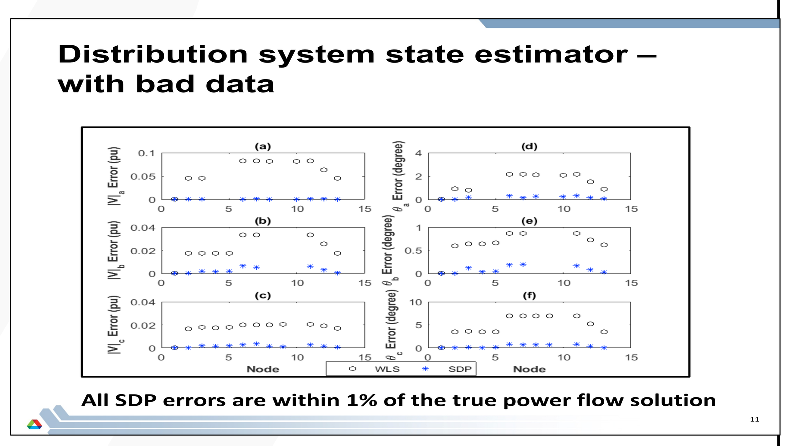
T&D Steady-State Analysis



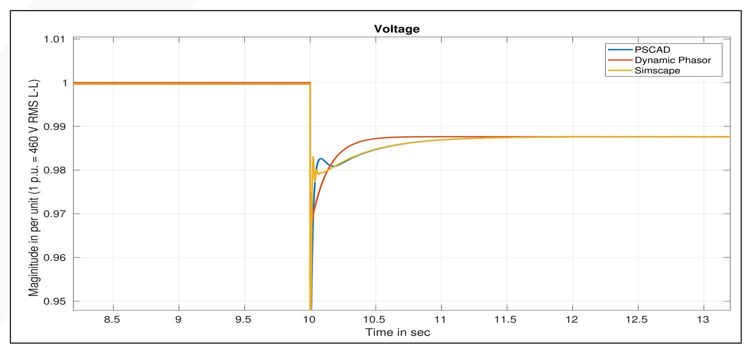
T&D Dynamics and Protection



Distribution State Estimation



PV phasor model



- Utility Advisory Group (UAG): Hawaiian Electric Company (HECO), Pacific Gas & Electric (PG&E), SouthWest Power Pool (SPP)
- Use cases (seven in total) for analyzing reliability and improving of combined transmission-distribution under high solar penetration.
- Publications:

- B. Palmintier et al., “Experiences integrating transmission and distribution simulations for DERs with the Integrated Grid Modeling System (IGMS)”, in Proceedings of the 19th Power Systems Computation Conference (PSCC’ 16) Genoa, Italy 2016.
- A. Flueck, “A Tool-Suite to Improve Reliability and Performance of Combined Transmission-Distribution under High Solar Penetration”, presented at the CAPE Users group meeting, Ann Arbor, Michigan 2016.
- K. Balasubramaniam and S. Abhyankar, “A Combined Transmission and Distribution System Co-Simulation Framework for Assessing Impact of Volt/VAR Control on Transmission System”, to appear in IEEE PES general meeting 2017.

Providing Ramping Service with Wind to Enhance Power System Operational Flexibility

GRID MODERNIZATION INITIATIVE
U.S. Department of Energy

Project Description

This project aims to develop an innovative, integrated, and transformative approach to mitigate the impact of wind ramping by providing flexible ramping products from wind power.

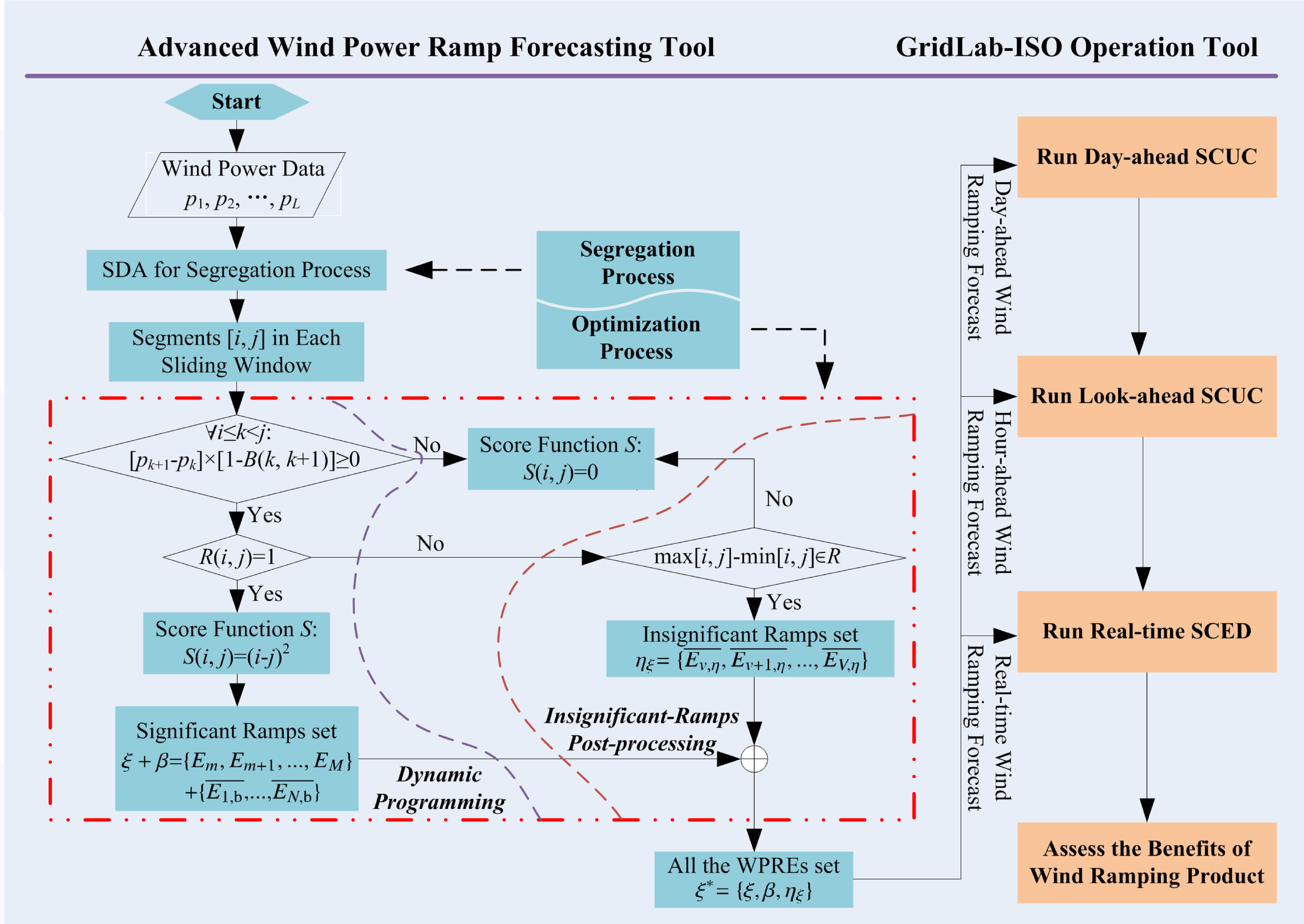
Expected Outcomes

- ❑ A new design to transform a negative characteristic of wind power, specifically "ramping", into an advantageous one.
- ❑ Advanced techniques for mid-term and short-term wind power ramp forecasting, including probabilistic forecasting.
- ❑ New tools, concepts, and techniques that can be licensed to utility companies for testing the benefits of using wind to providing ramping service.
- ❑ Collaborate with industry to test and validate the methodology, taking into account economic and reliability goals, by integrating the proposed wind ramping product into the operations of ISOs.

Impacts:

- ❑ The proposed project will significantly contribute to the reduction of wind integration costs by making wind power dispatchable and allowing the efficient management of wind ramping characteristics. This will also improve system reliability and economics, by reducing generation scarcity events and the associated price spikes.
- ❑ The new market simulation tool we design in this project will be open-sourced to all DOE labs, U.S. utilities, ISOs, power system researchers, and public.

Significant Milestones	Date
Develop new techniques for short-term (e.g. 5-min) wind power ramp forecasting.	12/31/2016
Assess wind ramping forecast performances at different forecasts horizons.	3/31/2017
Design the wind-friendly flexible ramping products.	6/30/2017
Create an open source electricity market simulation tool.	9/30/2017
Simulation of the proposed approach on 2000-buses ERCOT system	3/31/2018
Analyze the benefits of the proposed wind-friendly ramping product to the power grid using 2000-buses ERCOT system	9/30/2018



The Wind Power Ramp Forecasting and Electricity Market Simulation Tool Framework

Progress to Date

- Finished developing mid- and short- term wind power ramp forecasting algorithms and assessing their forecasting performance (including for probabilistic forecasts)
- Developed an Python based open source design of the electricity market simulation tool.
- Peer-reviewed articles (FY18): 2 conference and 3 journal articles

1. X. Fang, B. Hodge, V. Krishnan, F. Li, "Potential of Wind Power to Provide Flexible Ramping Products and Operating Reserve," *IEEE Power & Energy Society General Meeting*, Portland, OR, Aug. 5-9, 2018
2. K. Sedzro, X. Fang, B. Hodge, "Analysis of Wind Ramping Product Formulations in a Ramp-constrained Power Grid," Haiwaii International Conference on System Science, Jan. 8-11, 2019.
3. X. Fang, V. Krishnan, B. Hodge, "Strategic Offering for Wind Power Producers Considering Energy and Flexible Ramping Products," Energies, 11(5), 1239.
4. X. Fang, B. Hodge, E. Du, N. Zhang, F. Li, "Modelling Wind Power Spatial-Temporal Correlation in Multi-Interval Optimal Power Flow: A Sparse Correlation Matrix Approach," under review by Applied Energy
5. X. Fang, M. Cui, B. Hodge, F. Li, "Strategic Day Ahead Wind Offering Considering Both Wind and Prices Uncertainties," under review by IEEE PES Letters.

U.S. DEPARTMENT OF ENERGY

Principal Investigator: Bri-Mathias Hodge, National Renewable Energy Laboratory
Team members: Xin Fang and Kwami Sedzro (NREL)
External Partners: The University of Texas at Dallas

Sept. 5, 2018